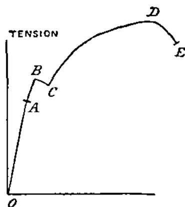
extremely straight, and the stresses and strains are almost exactly proportional. Between A and B a sensible, but slight, curvature appears in the diagram, and a sensible, though small, deviation from proportionality begins to appear in the stresses and strains. Bauschinger calls the point A the limit of proportionality, but it would be better to call it the elastic limit. A little beyond the elastic limit, at B, there is, for some rolled or hammered materials, a very singular and marked jump, or inflection B C in the stress-strain diagram. This point is very clearly marked in the diagrams of the Committee of Civil Engineers appointed to make experiments on steel,[1] and is shown in Fig. 24, which is a plotting of two of their experiments on steel. The Committee call this point the 'yielding point.' The behaviour of the material at this point was very accurately described by Bauschinger in 1879,[2] and he adopted for it the term 'Streckgrenze.' Bauschinger indicated the very great suddenness of the increase of extension, lateral contraction, and temperature. In 1881 Prof. Kennedy, in a Report on Riveted Joints to the Institute of Mechanical Engineers, called attention to this peculiarity in rolled steel, and gave to

Fig 27



[1] *Experiments on Steel*, 1870   [2] *Civilingenieur*, Bd xxv s. 81.

the point A the name 'breaking-down point.' On the whole this term seems very suitable, if by breaking down is understood a breaking down of the primitive molecular arrangement.

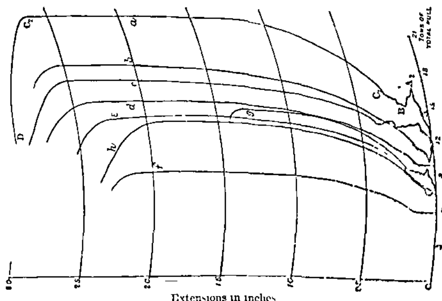
The phenomenon of breaking down is not due to any action of the testing machine, for it is shown in diagrams from a machine in which the load is automatically adjusted to the resistance of the bar, and in machines in which the loading is effected entirely by hydraulic pressure. Probably the breaking-down point is a kind of physical record of the condition of constraint in the bar at the moment of rolling or hammering. Not that the stress at the breaking-down point is identical with the stress in rolling, for the temperature conditions are different in rolling and testing. But still, it is probable that at the breaking-down point a mechanically produced condition of aggregation is passed, and the artificially-created rigidity suddenly gives way.

Beyond the inflection at the breaking-down point the partly plastic, partly elastic, extension proceeds regularly again. But the precise extension for any load between B and C depends more or less on the time during which the load acts. During any pause in this part of the curve the extension increases without increase of load, and when the load is increased again the rigidity of the bar is found to be greater than before, and the curve becomes steeper (Figs. 35, 39). Next to the breaking-down point the most important point to observe is the point D, where the maximum load is

reached. For this point it would be convenient to have a name, and, by analogy with elastic limit, the term 'plastic limit' may be proposed. This implies, what seems to be the case, that at the point C the pressure of fluidity is reached for the part of the bar at which fracture ultimately occurs. It is probably at the point C, or very near it, that the local contraction begins which is so characteristic of the last stage of testing of ductile materials.

30. *Form of the Stress-strain Curve at the Yield Point.* The form of the stress-strain curve near the yield

Fig 28



point is very variable, being greatly affected by small stress differences and by differences in the time rate of extension. Further, in most autographic arrangements

the record of stress is affected, when the specimen is yielding rapidly, by the inertia of the load. In Professor Kennedy's autographic apparatus the effect of the inertia of the load is eliminated, and Fig. 28 gives some autographic diagrams taken in this apparatus. It is difficult to believe, however, that the irregular curves near the yield point are not due to time differences, or perhaps to small stress differences arising out of the inertia of the elastic system formed by the test bar and testing machine. The diagrams are, however, the most satisfactory autographic diagrams yet obtained.[1]

31. *Behaviour of a Ductile Material when broken by Tension; Local Drawing Out, or Local Contraction.*—A bar or plate of ductile material such as soft steel is placed in the testing machine and subjected to a gradually increasing stress till it is broken. At first, as the extensions are small, it is easy to keep the lever of the testing machine floating with almost any rate of loading. At the yielding point, however, the stretching suddenly becomes rapid, and with most testing machines it is not possible to keep the lever floating. The lever can only be kept floating if the pumps which work the hydraulic press are capable of moving the press ram as rapidly as the rate of increase of stretch. With a single-lever testing machine the author finds it possible in most cases, but not always, to just keep the lever floating during the

[1] In Professor Kennedy's diagrams the ordinates are curved:—*a* is a diagram for a Swedish iron bar; *b*, Shelton bar iron; *c*, Swedish iron; *d*, Landore rivet steel; *e* and *f*, Landore steel plate; *g*, cast steel; *h*, mild-steel bar.

stretching at the yielding point, but to do this it is often necessary to run the weight back a little to diminish the stress. When the rapid stretch at the yielding point is ended, and the bar has again become capable of supporting an additional stress, it is quite easy, in general, to adjust the rate of loading so that the press just takes up the stretch, and the lever remains floating almost without movement. And this continues till the maximum load is reached. Beyond that point the drawing out of the specimen at a restricted portion of its length begins, and the reduction of area is so rapid that the stress must be diminished. It is here again difficult to keep always the lever floating. Finally, the bar breaks suddenly with a load considerably less than the maximum load it was sustaining just before the local drawing out commenced.

Suppose the bar ruled with straight lines at right angles to the direction of the stress. As the bar stretches the distance between these lines increases, but, so far as can be judged, they remain straight and parallel during the increase of stress till the maximum load is reached. During the local drawing out the lines become curved in the part which is drawing out. The line exactly at the centre of the part which is drawing out, however, remains straight. Professor Kennedy[1] has inferred from this curvature of the lines that the stress becomes very ununiform on the section of fracture, being greatest at the centre of the bar. Some slight

[1] *Proc. Inst. Mech. Eng.* 1881, p. 218.

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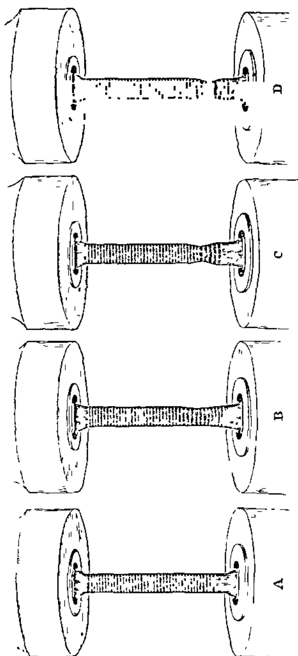
[1] *Proc Inst. Mech Eng* 1881, p 218

variation of stress probably is produced, but the author doubts if the variation is at all large. In fact, the extension measured along the curved edges of the bar is not very different from the extension at the centre, and if the material is plastic great variation of deformation is possible with small variation of stress.

Fig. 29 is from photographs of a strip of mild-steel plate taken during the process of testing. A was taken just when the maximum load was on the bar. No beginning of the drawing out is visible, and the lines drawn on the bar are still straight, as far as can be observed. Fig. B was taken just after the drawing out became visible, and when the stress on the bar had been a little diminished. At the centre of the part drawn out the line is still accurately straight, but the lines on each side are curved. Fig. C was taken at the very moment before fracture. The drawing out is here more considerable. Fig. D is the bar after fracture.

32. *Distribution of Drawing Out along the Bar.*—If a bar is divided into inch lengths before testing, and these are measured again after the bar is broken, the plastic extension in each inch length will be determined. It will be found that the amount of extension is more or less irregular along the bar. In the inch length in which local contraction and fracture occur the extension is very great. On either side it diminishes, at first rapidly, afterwards more slowly, and is least near the enlarged ends at which the specimen is held. But there are irregularities, showing that there are differences of

FIG 29



Drawing out of Mild Steel

plasticity along the bar, and in rare cases two local contractions form at different parts of the length. It is possible that some of the irregularities are due to the fact that the elongation is usually measured on one side of the bar only. It is desirable that the measurements should be taken on opposite sides of the test bar and averaged.

The following table gives some measured values for different materials :—

ELONGATIONS IN ONE INCH LENGTH OF BAR AT DIFFERENT DISTANCES FROM THE FRACTURE.

(The elongation in the division in which fracture occurred is indicated in italic type)

Material	Inches along the Bar											
	1	2	3	4	5	6	7	8	9	10	11	12
Lead . . .	0·18	·15	30	17	14	·22	·16	·17	*1·01*	—	—	—
Brass . . .	0·23	·20	20	*·30*	·21	22	*24*	21	21	·21	—	—
Wrought iron :												
Angle iron .	0 05	06	06	06	06	·065	·07	08	*·135*	08	—	—
Channel iron .	0 09	·11	08	10	*·23*	·14	·11	10	·10	09	—	—
Rivet iron .	0·17	·195	·23	*·51*	·26	23	·25	·23	·23	·18	—	—
Square bar .	0 24	22	22	·22	·21	27	*50*	*50*	26	·18	17	17[1]
Flat bar . .	0·11	*16*	·14	·10	·10	10	10	·10	·10	—	—	—
Steel :												
Steel plate .	*0·70*	·30	·22	·19	·19	·15	·15	·16	—	—	—	—
Steel axle .	0 16	·17	·21	21	·18	17	21	*65*	·46	·17	13	·10[2]
Steel tire .	0 02	·06	08	21	*67*	·22	05	02	·03	·06	08	*12*[2]

It follows that the ultimate extension, reckoned as a percentage of the length of the bar, varies as the length is greater. Thus, taking the square wrought-iron bar,

[1] H. R. Towne.
[2] Steel Committee. The other measurements are the author's.

and taking lengths symmetrically situated with respect to the fracture, the ultimate extension per cent. is—

In two inches, including fracture	50 per cent
In four inches	38 ,, ,,
,, six ,,	32 ,, ,,
,, eight ,,	29 ,, ,,
,, ten ,,	27 ,, ,,
,, twelve ,,	26 ,, ,,

But not only does the ultimate extension depend on the length measured, it depends also, in bars of a given length, on the position of the fracture. It is desirable for comparative purposes to calculate the extension for all bars in such a way as to give the nearest approximation to the extension of a bar which broke at the centre of the measured length. Thus the ultimate extension of the rivet-iron bar in a length of ten inches is best obtained thus—

Extension in fourth inch (fracture)	0 51
Extension in divisions 1, 2, 3, 5, 6, 7	1 335
Double extension in division 8	0 46
Extension in division 9	0 23
Extension in ten inches symmetrical with fracture	2 535
Elongation per cent , 25 35	

This has not been the usual method of calculating the ultimate extension, but it obviously gives results more comparable than the usual method, and it has been recommended for adoption by the German testing laboratories. Further results on the variation of extension with distance between gauge points will be given in the chapter on the form of test pieces.

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	1	2	3	4	5	6	7	8	9	10	11	12
Lead . . .	0·18	15	30	17	·14	·22	16	17	*1·01*	—	—	—
Brass . . .	0 23	20	·20	*·30*	·21	·22	·24	·21	·21	·21	—	—
Wrought iron :												
Angle iron .	0 05	06	·06	06	06	065	07	08	*·135*	08	—	—
Channel iron .	0 09	·11	08	·10	*·23*	·14	11	·10	·10	·09	—	—
Rivet iron .	0·17	·195	·23	*·51*	26	23	25	·23	·23	·18	—	—
Square bar .	0 24	22	22	22	·21	27	*50*	*50*	·26	·18	17	17 [1]
Flat bar . .	0·11	*·16*	·14	·10	·10	·10	·10	10	·10	—	—	—
Steel :												
Steel plate .	*0 70*	30	22	19	·19	·15	·15	·16	—	—	—	—
Steel axle .	0·16	·17	·21	·21	18	17	·21	*·65*	·46	17	13	10 [2]
Steel tire .	0 02	06	08	·21	*·67*	·22	·05	02	·03	·06	·08	·12 [2]

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This has not been the usual method of calculating the ultimate extension, but it obviously gives results more comparable than the usual method, and it has been recommended for adoption by the German testing laboratories. Further results on the variation of extension with distance between gauge points will be given in the chapter on the form of test pieces.

hardly be considered to have been absolutely established, but the following results show that it is at least a good approximation :—

Identity of Percentage of Elongation in Similar Bars (Barba).

A billet of extra soft steel was hammered to an octagon of 3¼ × 3¼ inches, rolled to a bar 1¼ inch diameter and annealed. Three test pieces gave the following results.—

Diameter, inches	Lengths between gauge points, inches	Length / Diameter	Limit of elasticity, tons per sq. in.	Breaking stress, tons per sq in.	Elongation per cent
·787	7·87	10	15·72	23·85	31·0
·394	3·94	10	15·68	23·35	30·5
·197	1·97	10	15·72	23·90	31·4
Means			15·71	23·70	31·0

Experiments on Two Harder Qualities of Steel, rolled to Bars $1\frac{9}{16}$ inch Diameter and Annealed

Diameter, inches	Lengths between gauge points	Length / Diam.	Limit of elasticity, tons per sq in	Breaking stress, tons per sq in	Contraction per cent.	Elongation per cent
·272	1·97	1 to 7·24	15·22	26·77	69·3	32·8
407	2·95		15·22	26·65	69·0	33·2
543	3·94		15·34	26·70	69·7	33·0
679	4·92		15·16	26·45	68·6	33·5
815	5·91		15·10	26·40	69·2	33·6
·950	6·89		15·22	25·95	69·7	33·2
1·090	7·87		15·28	25·40	68·8	33·0
1·22	8·86		15·22	25·11	69·5	34·0
Means			15·22	26·20	69·2	33·3
·272	1·97	1 to 7·24	20·76	41·11	36·5	20·0
·407	2·95		23·21	41·20	38·0	18·8
·543	3·94		22·65	40·50	37·4	18·2
·697	4·92		24·10	40·17	38·4	18·1
·815	5·91		25·76	40·30	31·8	18·0
·950	6·89		24·16	39·34	35·8	18·1
1·090	7·87		24·16	40·10	34·4	19·5
1·22	8·86		—	—	—	—
Means			23·53	40·35	36·1	18·6

EXPERIMENTS ON PLATES

Dimensions of test bar		Width / Thickness	Length between gauge points	Length / √area	[illegible]	[illegible]	[illegible]
Width	Thickness						
·787	·197	4 to 1	1 97	5	10 67	23 00	[illegible]
1 575	·394		3 94	5	10 86	24 25	[illegible]
2 362	·591		5 91	5	13 14	24 70	[illegible]

33. *Suppression of the Drawing Out.*—The drawing out in ordinary test bars is measured on a portion of uniform section, and the measurements are not extended quite up to the enlarged ends by which the specimen is held. The enlarged ends diminish the drawing out of the parts nearest them, and if the part between the enlarged ends is very short the drawing out, contraction, and strength are all affected. For the present, cases will be considered in which the change of section is gradual not abrupt

A plate perforated with a row of holes, or formed like B or C (Fig. 31), is virtually a very short test bar. In reporting on riveted joints for the Institute of Mechanical Engineers,[1] the author noticed that in some cases a perforated plate was stronger than a plain test bar of the same material. Shortly after, this was shown more distinctly in some experiments of the Board of Trade on riveted joints,[2] and in experiments by Professor Kennedy for the Institute of Mechanical Engineers. In these last experiments, perforated steel plates ¼ inch

[1] *Proc Inst of Mech Engineers*, 1881, p 319

[2] *Experiments on Steel* Memorandum of the Board of Trade, 1881, p 18

of the contraction of area by the neighbourhood to the breaking section of less strained material. Now, as the breadths at corresponding points of B and C are exactly equal, it looks, at first sight, as if B and C ought to behave exactly alike, whereas, apparently, in the experiments B is stronger than C. It will be seen, however, that the material near the point of fracture is not in identical conditions in the cases B and C. Suppose two bars of the form D are placed back to back and broken. The material at the place of fracture is now identically in the same state as in form C, and contraction takes place not only round the semicircular holes, but along the edges *m m*. Weld together the pieces along this line, and the contraction along *m m* can no longer occur. The piece is then identical with form B, it has less contraction than C, and ought to be stronger The experiments show that it is so.

Mr. Richards made a very interesting series of experiments at the Barrow Company's Steel Works on test bars similar to Mr. Strohmeyer's bars A and B. The material was mild steel made by the Siemens process. The plate was $\frac{1}{2}$ inch thick. Two pieces had parallel sides like ordinary test bars. The other specimens were indented on each side by a semicircular drilled hole, leaving a section between of varying width. The results are given in the following table.

Here the plates of form B, equivalent to perforated plates, are on the average 12·6 per cent. stronger than the parallel-sided bars of form A, and the strength is

Form	Width b inches	Thickness t	Contraction of area per cent	Contraction of width per cent	Contraction of thickness per cent.	Breaking stress in tons per sq in.
A	1	495	52 5	27 0	33 3	32 01
	1	490	53 5	27 5	35 9	32 47
B	645	495	45	19	32	36 64
	·650	500	46	19	33	36 52
	·995	502	47	11	37	36 82
	995	495	42	12	34	37 05
	1 47	502	31	8	26	36 18
	1 46	50	36	10	30	35 88
	2 28	495	42	9	36	35 72
	2 27	·495	43	8	37	35 72

very uniform considering the different widths of the specimens. The contraction of area in form A is 53 per cent., while in form B it is only 41 per cent., so that there is a diminished contraction to account for the increase of strength. Further, while the contraction of thickness is nearly the same in form A and form B, the contraction of width, which is what would be affected by the form of the specimen, is 27·2 per cent. in form A, and only 11 9 per cent. in form B.

The shortest possible bar is formed by turning a groove with a very slightly rounded bottom. The following experiment on two bolts of Whitworth compressed steel gives the strength of a bar of extremely tough material thus shaped The heads and nuts of the bolts were turned to fit spherical seatings, so that the stress was quite fairly applied. A groove, a little rounded at bottom, precisely like a Whitworth screw thread, was turned in the body of one bolt as at A (Fig. 32), and the other was turned in the form shown at B.

	Diameter	Breaking load, in tons	Breaking stress, in tons per sq. in.
Form A .	1 560 .	. 101·77 .	. 53·25
„ B .	. 1·487 .	. 62 35 .	. 35 87

B elongated 60 per cent., and the contraction of area was 54·6 per cent. For A the elongation and contraction were practically *nil*.

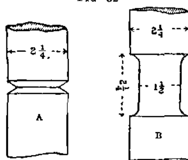


FIG 32

34. *Abrupt change of Section—Nicked Specimens.*—At any abrupt change of section the stress on cross sections cannot be uniform. The less strained metal hinders the extension of other metal near it. If the material were perfectly elastic the stress at any re-entrant angle would be infinite, but the plasticity of all ordinary materials diminishes very greatly the inequality of stress. Nevertheless the inequality exists, and it counteracts the gain of strength due to suppression of drawing out.

Two pieces of the same cast iron were tested, one in the form of an ordinary test bar, the other with a square collar in the middle of its length. The re-entrant angles at the collar were virtually nicks. The breaking weights were—

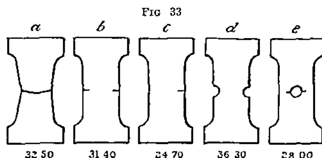
Plain bar . . .	. 13·875	tons per sq. in.
Collar bar .	11·980	„ „
Decrease	. 1·895	„ „

showing a loss of 13·6 per cent. of strength, due to

the inequality of distribution of stress caused by the collar.

Mr. Baker made some interesting experiments on steel plates with artificially produced cracks.[1] A fine saw-cut was made at one or both edges of the specimen, and then, raising the specimen nearly to welding heat, the saw-cut was closed up so far as to be rendered invisible. Fig. 33 shows a set of specimens of the same steel. Specimen *a* was an ordinary test

FIG 33



bar; *d* was a bar with semicircular notches, so that it was virtually a short bar; *b* was a bar with a saw-cut or crack on both sides; *c* a bar with a saw-cut or crack on one side; *e* a bar perforated with a crack on each side of the hole.

The breaking weights in tons per sq. in. are given under the figures. It will be seen that the short bar *d* is stronger than the plain test bar *a* by 3·8 tons, or 12 per cent.; but the nicked bar *b* is weaker by 1·1 ton, or $3\frac{1}{2}$ per cent. Considered as a short bar, *b* should have carried as much as *d*, the

[1] *Minutes of Proc of Inst of Civil Eng*, vol. lxxxiv. p 165.

inequality of distribution of stress has therefore reduced its strength by $15\frac{1}{2}$ per cent. Similarly *e* is weaker than *d* by 8 tons, or 22 per cent. It is clear, therefore, that, in the case of nicked bars, the increase of strength which would result from the virtual shortness of the bar is more than counteracted by the inequality of stress on the section of fracture. Mr. Baker found with specimens of indiarubber a loss of strength in nicked specimens of 60 or 70 per cent., and that is probably due to the fact that indiarubber, although it deforms enormously, is really less plastic than steel, and consequently the variation of stress is greater.

Relation of ultimate Elongation to Contraction of Area.—It is now common, in testing iron and steel by tension, to record the ultimate elongation in a length of 8 or 10 inches, and the contraction of area at fracture, as data useful for deciding on the value of a material. Both the ultimate elongation and the contraction are supposed to indicate the ductility of the material, and a good deal of confusion arises from the discrepancy between these two quantities.

It has already been shown (§ 23) that for a perfectly plastic material

$$\frac{\text{contraction of area}}{\text{initial area}} = \frac{\lambda}{l - \lambda},$$

that is, the percentage of contraction is equal to the percentage of elongation, calculated on the stretched

length of the bar. Hence, a definite relation between the elongation and contraction will only be found for the short length of the bar, which becomes almost perfectly plastic, and draws out during the last stage of the test. That a definite relation does exist between the elongation and contraction in the immediate neighbourhood of the fracture is easily shown. From the experiments on steel by a Committee of Civil Engineers, Tables A, B, C, D, it is possible to get the elongation in a length of 1 inch or 2 inches of the bar in the neighbourhood of the fracture, and to compare it with the contraction of area.

Material	No. of bar	Length, in inches l	Contraction / Initial area $\frac{\omega}{\Omega}$	Elongation / Stretched length $\frac{\lambda}{l+\lambda}$
Bessemer steel	943	2	32	·22
	1,194	2	55	·31
	1,285	1	44	·35
	1,028	1	58	34
	1,174	2	56	36
	1,305	1	37	30
	923	1	47	·35
	1,038	1	50	42
	1,184	2	44	32
	1,295	2	41	·27
	1,275	2	34	·27
	1,255	1	42	·30
	1,265	2	09	·09
Crucible steel	873	1	44	29
	1,078	1	37	25
	1,147	1	54	40
	1,068	2	03	03
Means			40	28

Here the agreement is as close as could be expected, the percentage of elongation (estimated on the stretched length) being three-fourths of the percentage of con-

traction of area. Had it been possible to measure the elongation in, say, a $\frac{1}{2}$-inch length, the approach to agreement would, no doubt, have been closer.

The following numbers are from some measurements by the author :—

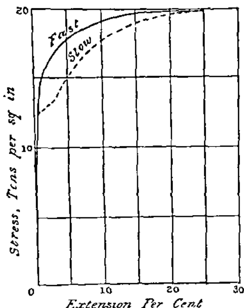
Material	Length l	$\frac{\omega}{\Omega}$	$\frac{\lambda}{l}$
Iron bar	2	·24	·20
,, .	2	·28	·20
,, ...	2	42	·27
Angle iron . .	2	·15	15
Iron plate	2	·12	11
Steel plate . .	2	·39	·29
Delta metal . . .	2	·09	·07
,, ,, . .	2	·27	32

If there is this near agreement in the contraction and elongation in the short, plastically-yielding part of the bar near the fracture, then there can be no agreement in the contraction and elongation in greater lengths of bar. The contraction does measure in a definite way the plasticity of the material under the breaking stress. The ultimate elongation in an 8- or 10-inch length measures partly the plasticity of a short length under the breaking stress, partly the plasticity of the rest of the bar before drawing out commenced. The two measures of the ductility are only in agreement when the elongation is taken for a very short length of bar near the fracture.

35. *Influence of Time on the Stress-strain Curve.*—It has been seen that plastic yielding is gradual, either increasing indefinitely or at a diminishing rate under a

given stress. Hence it might be expected that the plastic part of the stress-strain curve would be flatter the slower the rate of loading. Professor Ewing gives the stress-strain curves shown in Fig. 34 for two similar pieces of soft-iron wire, one loaded to rupture in four minutes, the other at a rate about 5,000 times slower.

FIG 34.



In the same way, in taking autographic stress-strain diagrams there is a notch in the diagram at any pause in the increase of loading. Fig. 35 shows a diagram for a manganese steel bar, tested with a pause of five minutes at each successive ton.

Fig. 36 shows the stress-strain curves for four pieces of wrought iron cut from the same bar. For bar 319 the extensions were measured on a length of $4\frac{1}{2}$ inches; for the other bars on a length of 9 inches. In the case of bars 319 and 154 the extension increased at a nearly uniform rate during the plastic stage. In the case of bar 313 there were four-minute pauses at each successive ton, and the diagram is notched. In the case of bar

FIG. 35.

Load Tons

20

15

10

5

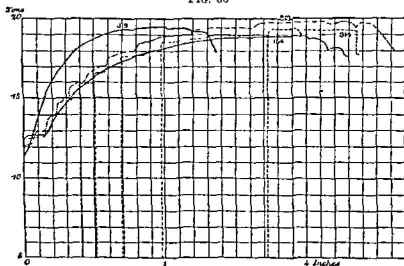
0

1

2 Inches

Extension in 8 inches

FIG. 36



314 the load was taken off and a pause of six minutes allowed at each successive ton. It may be noticed that

the breaking-down point is more marked with the longer bars. The following table gives a summary of the tests :—

No. of bar	Tons per sq. in.		Elongation per cent
	Yield point	Maximum load	
319	12·97	22·19	34·7
154	14·37	22·10	25·8
313	13·68	22·34	29·5
314	14·23	22·47	28·2

36. *Influence of Time on the ultimate Elongation.*—Some remarkable experiments of Colonel Maitland at Woolwich[1] show that, contrary to a common prejudice, the ultimate elongation is increased by very rapid loading. Colonel Maitland experimented on a steel which, in unhardened specimens of 2 inches in length between shoulders, broke in the testing machine at 26 tons per sq. in. and with 27 per cent. of elongation. A specimen was then screwed into blocks arranged so as to fall vertically in a slide. After a certain height of fall the top block was arrested by stops and the specimen broken by the momentum of the lower block. Broken in this sudden way the ultimate elongation was 47 per cent. Specimens were then screwed into plugs fitting a strong tube and broken by exploding gunpowder and guncotton between the plugs. The plugs were driven out in opposite directions, breaking the specimen connecting them. Under these circumstances the ultimate elongation was

[1] 'The Treatment of Gun Steel.' *Proc. Inst. of Civil Engineers*, vol. lxxxix. p. 120.

ω sq. ins. section, $a\,b$ will measure on a scale ω times that for the loads the stress per sq. in. of initial section of the bar. Up to the yield point the section of the bar changes very little, but beyond the yield point the deformation is so large that the section sensibly changes. Then $a\,b$ does not represent the stress per sq. in. of the actual section of the bar at the moment. To find this it is approximate enough to consider that the change of density is small compared with the deformation. Hence, so long as the deformation is general over the marked length of bar—that is, up to the maximum load point i, the section of the bar can be found from the measured length.

Let l, ω be the length between gauge points and section of the bar initially, and $l\,(1+\lambda)$ and ω_1 the length and section when the load is P. Then, $\omega\,l = \omega_1\,l\,(1+\lambda)$,

$$\omega_1 = \frac{\omega}{1 + \lambda}.$$

If p is P/ω, the stress reckoned on the initial section, then the real stress on the actual section is—

$$p_1 = \frac{P}{\omega_1} = p\,(1 + \lambda).$$

In the diagram take $O\,C = l$ to the same scale as that on which $O\,a = l\,\lambda$. Draw $b\,d$ horizontal. Through d draw $C\,d\,e$, cutting $a\,b$ in e. Then $a\,e$ represents p_1, the actual stress on the reduced section, to the same scale as that on which $a\,b$ represents p, the stress calculated on the initial section. If several points are thus

found we get a curve $f e g$, lying above the ordinary stress-strain curve and extending to the point of maximum load. This is sometimes called the curve of true cohesive strength. It is simply a curve giving the relation of the actual stress and strain.

Beyond the point of maximum stress the construction fails, for the extension becomes chiefly local and the l in the formula above is no longer the length between the gauge points. But another point in the curve may still be found. If the contracted section is measured after the bar is broken, then the breaking load $h k$ divided by that section gives the real stress $k m$ at the moment of fracture. It is obvious, however, that the part $g m$ of the curve is distorted, for while the abcissæ up to the point i represent extensions of a fixed length l, the abcissæ from i to h represent extensions of an undetermined portion of l. The real elongation per unit of length at the moment of fracture in the part which is drawing out is given by the equation—

$$\lambda_1 = \frac{\omega - \omega_1}{\omega_1};$$

and if $O k'$ is taken equal to $l \lambda_1$, and $k' m'$ set off equal to $k m$, the general form $g m'$ of the final portion of the real stress-strain curve is determined. It is quite possible to measure the contracted section at intermediate loads between i and h during testing and to calculate intermediate points along $g m'$. So far as can be judged from one or two instances, the portion $g m'$ of

and 64·4 mm. in height. The following table gives the loads and compressions :—

CRUSHING OF A LEAD CYLINDER (KICK).

Load, in tons	Height, in inches	Compression, in inches	Diameter at centre, in inches	Stress, in tons per sq in of central area
—	2 576	—	2 00	—
2 9	2 312	·264	2·16	79
3 25	1 904	672	2·40	·72
3 35	1 716	·860	2 52	·67
3 45	1 636	930	2 60	65
3 95	1 376	1 200	2 84	62
5 65	1·128	1·448	3 16	72

It appears that the pressure of fluidity was reached at about 0·75 tons per sq. in., and the stress remained approximately constant notwithstanding the large deformation.

Fig. 38 shows a similar curve for a wrought-iron cylinder. The experiment was made by Fairbairn, and the results are discussed in Cotterill's 'Applied Mechanics,' p. 418.

Plastic Compression of Copper Cylinders.—Small copper cylinders made of the softest and purest copper are used in crusher-gauges for determining the powder pressure in the bore of the gun. The copper cylinders are made in two sizes, $\frac{1}{24}$ sq. in. and $\frac{1}{12}$ sq. in. in section, and the initial length is 0·5 inch. Tables have been published[1] giving the compression of these cylinders when compressed by hydraulic pressure, the compressions being measured by a Whitworth measuring machine.

[1] *Industries*, March 25, 1887.

COMPRESSION OF SOFT-COPPER CYLINDERS

Cylinder initially 0·5 in. long and $\frac{1}{24}$ sq. in. area				Cylinder initially 0·5 in. long and $\frac{1}{12}$ sq. in. area			
Compression, in inches λ	Compressed length, in inches $l-\lambda$	Pressure, in lbs. P	Pressure per sq. in. of compressed area, in tons	Compression, in inches λ	Compressed length, in inches $l-\lambda$	Pressure, in lbs. P	Pressure per sq. in. of compressed area, in tons
·10	·40	2,091	17·9	·10	·40	4,000	17·1
·11	·39	2,225	18·7	·11	·39	4,333	18·1
·12	·38	2,359	19·3	·12	·38	4,666	19·0
·13	·37	2,494	19·8	·13	·37	5,000	19·8
·14	·36	2,628	20·3	·14	·36	5,333	20·5
·15	·35	2,763	20·7	·15	·35	5,666	21·2
·16	·34	2,897	21·1	·16	·34	6,000	21·8
·17	·33	3,031	21·4	·17	·33	6,333	22·3
·18	·32	3,162	21·6	·18	·32	6,666	22·8
·19	·31	3,296	21·9	·19	·31	7,000	23·2
·20	·30	3,431	22·1	·20	·30	7,333	23·5
·21	·29	3,565	22·2	·21	·29	7,666	23·8
·22	·28	3,700	22·2	·22	·28	8,000	23·9
·23	·27	3,834	22·1	·23	·27	8,333	24·0
·24	·26	3,968	22·1	·24	·26	8,666	24·0
·25	·25	4,103	22·0	·25	·25	9,000	24·0
				·26	·24	9,333	24·0
				·27	·23	9,666	23·7
				·28	·22	10,000	23·5
				·29	·21	10,333	23·2
				·30	·20	10,666	22·8
				·31	·19	11,000	22·4

The preceding table gives the compressions λ, compressed length $l - \lambda$, and observed pressure producing the compression. Neglecting the barrel-shaped distortion the stress reckoned on the deformed prism is—

$$p_1 = P\frac{l - \lambda}{\omega\, l},$$

and the values of this have been calculated and placed in the tables. When the material is completely plastic, p_1 is the pressure of fluidity.

It will be seen that for compressions exceeding two-fifths of the original length the pressure on the actual deformed section is nearly constant. Further, the numbers for the cylinder of $\frac{1}{12}$ sq. in. area are almost exactly double those for the cylinder $\frac{1}{24}$ sq. in. area. According to both tables the pressure of fluidity for soft copper must be about 22 tons per sq. in.[1]

39. *Raising the Elastic Limit by Stress.*—It has long been known that for iron, steel, and other metals a load exceeding the elastic limit raises that limit. Thus, Bauschinger gives the following results of experiments on five gun-metal bars, of a section about 2·8 × 0·5 inches. The elongations were measured in 8 inches by the mirror apparatus :—

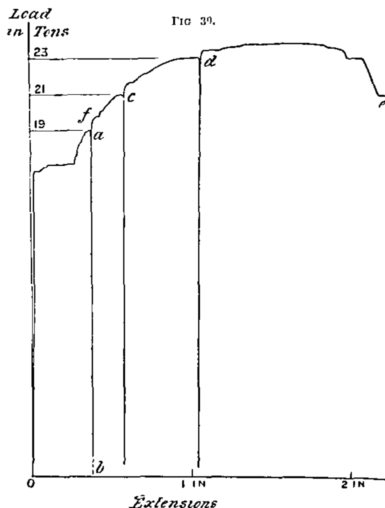
No. of bar	Original elastic limit, in tons per sq. in.	Stress applied, in tons per sq. in.	Permanent set, in inches	Raised elastic limit, in tons per sq. in.	Tenacity, in tons per sq. in.
1	4·62	6 56	·00061	6·15	14·2
2	3 82	6 10	·00061	5 74	14 9
3	3 84	6 56	00067	5 77	13 3
4	3 50	5 85	00054	5·80	12 9
5	3 77	6 02	·00057	5·66	13 2

[1] See also *Treatise on the Manufacture of Guns* (official), p. 92.

In these experiments the second loading was effected only a few minutes after the first loading.

Bauschinger noticed that if a bar after loading beyond the elastic limit was left for twenty-four hours

FIG 39.



or more at rest it recovered partially the set previously taken, and if then the elastic limit was again determined

it was in some cases raised not only up to but beyond the load previously applied.

Fig. 39 shows a stress-strain diagram of a piece of steel plate, taken autographically by apparatus which will be described. The yielding point, or breaking-down point, is strongly marked at a load of about 18 tons. At 19 tons, 21 tons, and 23 tons the load was almost completely removed, the pencil tracing downwards and retracing upwards almost exactly straight lines parallel to the primitive elastic line. Thus, at 19 tons the pencil described while the load was removed and replaced the straight line *a b*. The distance *o b* represents the permanent set produced by the load of 19 tons, and the stress-strain diagram for the material altered by loading is the line *b a c* . . . . Similarly for the other points at which the load was removed. The peculiarity specially to be noted, and which indeed is only shown in such autographic diagrams as this, is the steepness and almost straightness of the curve at *a f*. The material is not only nearly perfect in its elasticity in the reimposition of the load up to the point *a*, corresponding to a load of 19 tons, but is nearly perfect in elasticity to the point *f*, corresponding to a higher load. More accurately, *f* is a new yielding point in the material altered by loading.

Viscosity of Solids. Elastic After-Working.—If a wire carrying a heavy vibrator is set in vibration torsionally within its limits of elastic stress, the vibrations subside more rapidly than can be accounted for by

external causes or by heating effects. There must, therefore, be an internal molecular friction or viscosity. In a wire kept vibrating constantly more molecular friction is found than in one allowed to rest between each experiment[1]— that is, the arc of vibration diminishes more rapidly.[2] This is due to an 'elastic afterworking,' by which the strained metal recovers its original condition gradually during a period of rest. If the limit of elasticity has been exceeded, there is a still more marked change of the material after straining and during subsequent rest, due to elastic or plastic afterworking.

40. *Bauschinger's Experiments on the Influence of Rest after Drawing Out on the Elastic Limit.*—Bauschinger first indicated[3] that, by drawing out a metal by stress beyond its elastic limit, the elastic limit is raised, not merely during the continued action of the load, but during a period of some days after the load is removed. The elastic limit may in certain cases rise above the stress corresponding to the load imposed.

In a later paper[4] he gives a series of experiments on different metals loaded successively up to a point at which yielding just began. In one series, the successive

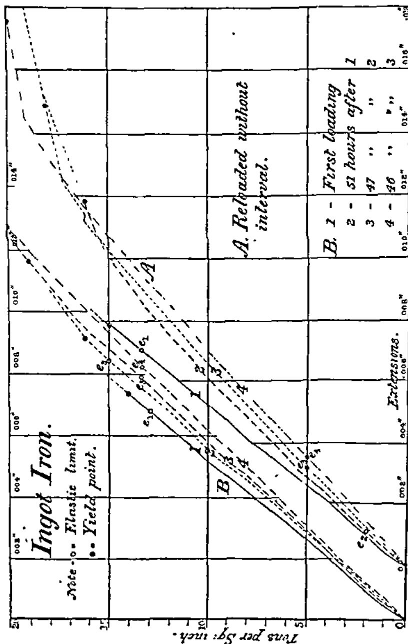
[1] Sir W. Thomson, *Proc. Roy Soc*, vol xiv 1865, p 289 Article, 'Elasticity,' in *Encyclopædia Britannica*, § 34

[2] Mr Tomlinson states that this fatigue of elasticity does not occur if the stresses are kept well within the elastic limit —*Trans. Roy. Soc.*, vol. clxxvii part 2, 1886

[3] *Dingler's Journal*, Bd 224, s 5

[4] 'Ueber die Veranderung der Elasticitatsgrenze,' *Civilingenieur*, 1881, s 290

FIG 40.



Ingot Iron.
Note -o- Elastic limit.
•• Yield point.
A. Reloaded without interval.
B. 1 - First loading
2 - 51 hours after 1
3 - 47 " " 2
4 - 46 " " 3
Extensions.
Tons per Sq: inch.

loadings followed each other immediately; in the other, a pause of one or more days was allowed after each loading before again loading. Generally the results were of the character indicated in the plotting of two series of the results in Fig. 40. Four stress-strain curves for each series are shown, plotted to a very large scale for the extensions, and each line extends up to the point (marked by a dot) at which yielding just sensibly commenced. The elastic limit (or exact limit of proportionality) is shown by a circle marked *e*.

In the series A the bar was reloaded without any sensible interval of time. The yield point rises at each loading but the elastic limit falls, in the second loading almost to zero. In series B an interval of about fifty hours was allowed between each loading. In this case the yield point rises as before, but the elastic limit rises also at each successive loading. Comparing the two series, it appears that the elastic or plastic recovery during the fifty-hour pause (unloaded) raised the elastic limit from the positions shown in A to those shown in B. Bauschinger's results seem to be expressed in the following conclusions :—

If a material is strained to or beyond the yield point, unloaded, and again immediately loaded :—

(*a*) The breaking extension is diminished, and the breaking load somewhat increased.

(*b*) The elastic limit is lowered sometimes to zero, and the modulus of elasticity is a little diminished.

(*c*) The yield point is raised to the stress corresponding to the previous load.

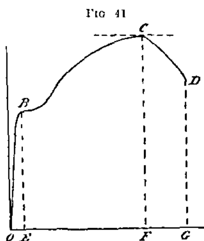
If after the first loading a period of quiescence is allowed before the second loading :—

(*a*) The elastic limit rises sometimes above its initial value.

(*b*) The yield point rises gradually above the stress corresponding to the previous load.

41. *Use of the Stress-strain Diagram in estimating the Work done on the Bar.*—Let Fig. 41 be a stress-strain diagram, the ordinates being as usual loads, in tons, on the section *a* of the bar, and the abcissæ extensions of a length *l* between gauge points. Draw verticals through B, C, D. Then, the work done on the bar up to the yield point is the area O B E, work done up to the plastic limit is O B C F, and work done in breaking the bar is O B C D G. The areas are easily measured by a planimeter. If *m* inches = 1 ton, and *n* inches = 1 inch of extension, then—

FIG 41



$$\text{Work in inch tons} = \frac{\text{area of diagram in sq. ins.}}{m\,n}$$

By dividing by the volume [illegible] the work per cubic inch of material. [illegible] already been said the elongation at [illegible] the same material with the length [illegible] and to a certain extent with the section of [illegible] is only with similar test bars that the work in breaking the bar, estimated per cubic inch of material, [illegible] furnish comparable numbers. But further, the [illegible] C D of the diagram is in most diagrams, if not in all, somewhat badly determined, and at any rate is extremely affected by time differences in the rate of extension. The work represented by F C D G is almost entirely work expended in local drawing out of the bar. If this is discarded, the area O B C F represents the work up to the plastic limit, at which, so far as carrying a load is concerned, the bar is virtually destroyed. If this is divided by the volume of the bar, values are obtained nearly independent of the dimensions of the bar, and therefore affording a good measure of its joint strength and ductility.

and nut afforded the only means of adjustment. In these cases it was necessary to remove or reduce the load while the adjustment of the abutment was made. Sometimes the load was lifted by a crab and tackle while the nut was screwed up.

To escape some of the difficulties of a lever arrangement a hydraulic press has been used to produce the stress in the specimen. The specimen being held at one end by a fixed abutment, the other is strained by attachment to the ram of the press, the movement of which takes up the deformation. In such machines the stress in the specimen must be inferred from the fluid pressure on the plunger, indicated by a pressure-gauge. Then, an allowance must be made for the friction of the cup-leather or packing of the ram. As this allowance is large, and varies with the condition of the ram and the packing, machines of this type are not susceptible of great accuracy.

According to experiments of Mr. John Hick, the friction of a press cup-leather on a ram d inches diameter, with a pressure of p lbs. per sq. in., is—

$$F = c\,d\,p,$$

where c is a constant. But the whole pressure on the ram is $\frac{1}{4}\pi d^2 p$. Hence, the fraction of the load on the ram expended in friction and not transmitted to the specimen is $4\,c/\pi\,d$; that is, it decreases as the diameter of the ram is greater. Hence, the proportional error likely to be introduced by miscalculation of the cup-

leather friction is less as the size of the ram increases. Machines of this type are, therefore, most suitable for testing test pieces of large section. However, the law of cup-leather or packing friction is not really known, and its amount is certainly extremely variable.[1]

It next appeared possible to combine the advantages of the hydraulic press machine and the lever machine in this way. The test bar was placed between a hydraulic press and a lever, or system of levers, acting as a steelyard. Roughly speaking, it may be said that in such a machine the stress is applied by the hydraulic press and measured by the steelyard.[2] All good modern machines are essentially arranged in this way, though in some screws and gearing are substituted for the hydraulic press, and in others a manometric arrangement is substituted for the steelyard.

43. *Machines for Testing in various ways Iron, Steel, and other Strong Materials.*—Machines for general testing purposes almost always now consist of :—

(1) A lever, or system of levers, with weights, forming a complete weighing apparatus. This is connected with one end of the specimen, and its purpose is to indicate from moment to moment the exact stress applied to the specimen. In a few cases, in place of the lever and weights a manometric apparatus is em-

[1] The friction in testing machine rams is certainly greater than Mr [illegible] ow speeds

[illegible] nah, in a

definitely assigned, nor is it easy to measure in an actual machine, except in the case of an unloaded machine. But there is no doubt that the sensitiveness attained in good machines is in excess of practical requirements. This point will be discussed later; but it may be pointed out that two specimens cut from the same plate quite commonly differ in strength by more than 1 per cent. Supposing the strength of the test bar to be 20 tons, 1 per cent. of this would be 4 cwt., and a reasonably good machine indicates differences of stress of far less amount than this. In most machines, probably, the sensitiveness varies with the load and increases as the load is greater. That is, the additional stress required to distinctly move the weighing apparatus becomes a less fraction of the load as the load increases. In a good 100-ton machine, carrying its full load, the lever will be distinctly moved by an addition to the stress of $\frac{1}{100}$ ton. That is, the sensitiveness is such that $\frac{1}{10000}$ of the load is indicated. This is equal to the sensitiveness of a good chemist's balance. The sensitiveness of machines with manometric apparatus may be made still greater.

(2) The machine must be accurate in the indications given—that is, the stress indicated by the machine must differ very little from the real stress. A sensitive machine may be inaccurate if the ratio of the leverage is imperfectly known, and it must be inaccurate if, from any flexure of the parts, the leverage changes with the load. Hence, it is of much more importance than has

generally been supposed that a testing machine should be so arranged that it can itself be tested. The weights used to load the lever can, of course, easily be standardised. But in many machines the leverage, or ratio of the weight applied to the stress on the specimen, has only been determined by measurement of the distances between the knife-edges, and very generally the original determination of the leverage by the maker is accepted as sufficient, however long the machine may have been in use. It is clear that, however carefully the leverage was determined in the first instance, the wear or displacement of the knife-edges may seriously alter it in course of time. If the fulcrum distance is 2 inches, a displacement of $\frac{1}{50}$ inch would introduce an error of 1 per cent. into all measurements made by the machine on the assumption that the leverage had remained constant.

The determination of the leverage of the machine by measurement of the knife-edge distance only is not satisfactory, and in machines used for scientific purposes direct means of testing the leverage by weighing should be provided.

(3) Facility of adjustment for different kinds of straining action, and for specimens of different dimensions. The importance of this quality in a machine depends very much on the kind of work it is intended to do. But it should be remembered that the shackles used for different kinds of stress are somewhat heavy and cumbrous, and the operation of changing the

arrangements for various kinds of work is somewhat laborious.

(4) Capability of easy and rapid manipulation during a test. In commercial testing it is of great importance that the testing should be accomplished rapidly. The means of gripping the specimen must be convenient, and often the manipulation of the weighing and hydraulic apparatus can best be effected by engine power.

(5) Autographic apparatus for registering the results is very convenient, and is a safeguard against errors in recording the results. Some machines are adapted, and others are not adapted, for the addition of autographic apparatus.

(6) It is very objectionable if, during a test, the specimen is subjected to shocks and vibrations.

Shocks or vibrations may arise either in the weighing apparatus (in adding loads, for instance); or in the hydraulic press (by the action of a pump); or, lastly, from the energy acquired by parts of the machine which move when the specimen more or less suddenly takes an increment of deformation.

Suppose a cubic inch of water suddenly forced into the hydraulic press by the pump. If the lever and weights had no inertia, no harm would result. But, in fact, the movement of the press ram induces a movement of the whole system, and the stress in the specimen is for the moment increased by the inertia of the whole system connected with it. If the specimen suddenly

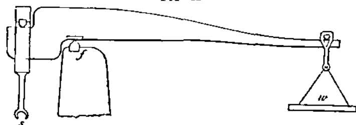
extends $\frac{1}{1000}$ inch, the weights on the lever move through a not inconsiderable distance. They acquire energy in falling, which again is expended in momentarily increasing the stress on the specimen.

The question whether a machine with small leverage or large leverage is likely to produce greater stresses in the specimen in consequence of its inertia has been a good deal discussed. If a specimen is loaded with a dead weight M, the inertia of the load reckoned at the specimen is M. But if the same specimen is put in a machine with a leverage n, with a load M/n producing the same stress, the inertia of the load reckoned at the specimen is $(M/n)\,n^2$, or $M\,n$. Hence it has been argued that the stresses due to shock increase directly as the leverage of the machine. All that the calculation shows is that, with a given velocity of movement at the specimen, the stored energy of the load liable to be expended in straining the specimen increases with the leverage. But the inference ignores the practical conditions in which testing machines are used. In proportion as the leverage of a machine is greater, its movements are more narrowly limited by the stops at the free end of the lever. The greater the leverage the more easily is any tendency to acquire velocity in the machine detected and controlled. Hence, practically, it is probable that the greater the ratio of the leverage, the less is the liability to unknown and prejudicial stresses due to inertia of the machine In the Buckton machine the maximum leverage is 50 to 1; in the Werder

machine it is 500 to 1; while in some compound-lever machines it is 20,000 to 1, or more. If the mere amount of leverage produced so serious an effect as that inferred above it would long ago have been detected in the use of the machines. In fact, however, in skilful hands, each machine is used in a manner suited to its construction and so as to reduce any action of this kind to a negligable amount.

46. *Arrangement of the Lever or Steelyard and Weights.* —In the oldest form of lever machine a bent lever

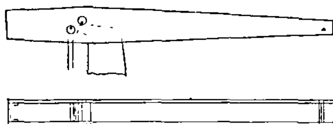
FIG 42



(Fig. 42) was used, the three principal knife-edges being in one straight line. The object of this arrangement was to secure a constant leverage notwithstanding some change of position of the lever. The leverage is the ratio of the perpendiculars from the fulcrum f on the directions of the load w and stress s, and if the knife-edges are not in one straight line the ratio of those distances sensibly changes with the alteration of inclination of the lever. In more modern machines the lever is left straight, and is formed of sufficiently rigid side plates (Fig. 43), between which are the knife-edges, fixed in rigid cross supports.

In the older machines and in some modern machines the loading is effected by placing separate weights in a scale-pan. Unless the leverage is large this is laborious, and, unless the lever is supported when weights are

FIG 43



added, shocks are produced on the specimen. Two modes of overcoming this difficulty have been found. In one the separate weights are successively added by mechanical arrangements; in the other a single travelling, or jockey, weight is rolled out along the lever. In the former, the leverage is constant; in the latter, the leverage varies as the jockey weight is rolled out.

Fig. 44 shows diagrammatically these arrangements. At A is the ordinary lever and scale; B and C are two arrangements in which jockey weights are used. In C the weight is so contrived that its centre of gravity lies in the line through the knife-edges. In order that the variation of position of the lever may not affect the stress on the specimen the centre of gravity of the lever must be on the line through the knife-edges, and the jockey weight must either have its centre of gravity on that line or must be hung from a knife-edge which travels on that line. At D is shown the mechanical

arrangement for adding weights to the lever. The weights are carried by a frame which can be *raised or*

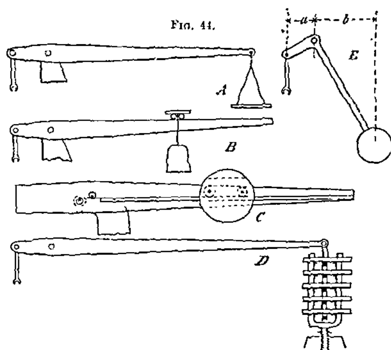


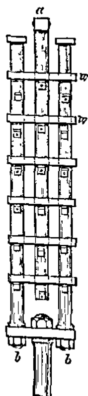
Fig. 44.

lowered by a screw. As the frame is lowered the weights are deposited in succession on projections upon the rod connected with the lever.

In Fig. 45 this mode of carrying the weights is shown in more detail. The central rod *a* is suspended from the lever. The side rods *b*, *b* are connected with a screw raising or lowering arrangement; *w*, *w* are the carefully-adjusted weights. When not in use the weights rest on lugs on the side rods *b*, *b*. By lowering *b*, *b* the weights are successively dropped without shock on the corresponding lugs on *a*.

There is one other arrangement of the lever which should be mentioned. In the testing machines of Thurston, Michaelis, and Polmeyer, a bent pendulum lever is used (E, Fig. 44), carrying a single heavy load. As the pull on the specimen is increased, the pendulum-bob moves outwards and upwards. If a and b are the perpendiculars from the principal fulcrum on the directions of the load and stress, the varying leverage is the ratio b/a.

Fig 45



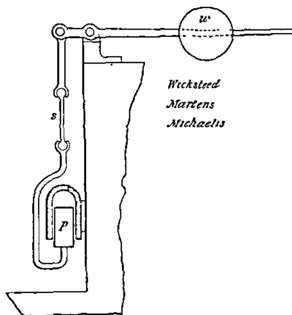
47. *Principal Types of Testing Machines.*—It is proposed in the following paragraph to indicate the principal types of testing machine which have been used as a key to the more detailed description of some of these machines which will be given later. It must be understood, however, that the figures are merely diagrams.

It will be seen that the most obvious arrangement is to place the weighing apparatus at one end of a specimen and the straining apparatus at the other. In fact, a large number of machines are thus constructed. Later, it appeared that certain advantages were obtainable by placing both weighing and straining apparatus at the same end of the specimen.

Simplest of all arrangements, probably, is that adopted first in a complete shape in the testing machine

at St. Chamond, and later adopted by Wicksteed, Martens, and Michaelis. In this machine (Fig. 46) the specimen *s* is held between a shackle attached to a horizontal weighing lever above and the ram of a

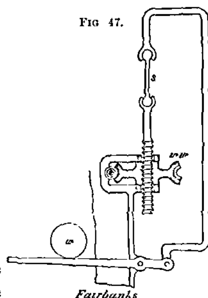
FIG. 46

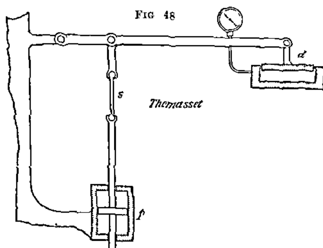


hydraulic press below. The weighing of the stress is effected by rolling out a jockey weight along the lever, or, in the Martens machine, by the arrangement shown in Fig. 45.

Somewhat similar is the arrangement of the testing machine of Messrs. Fairbanks & Co., of New York (Fig. 47). In this case a worm-wheel and screw are substituted for the press. The Fairbanks machine is virtually an ordinary platform weighing machine adapted

to the purpose of testing. It should be pointed out that, instead of the simple-lever system shown in this diagram, the actual Fairbanks machine has a compound-lever system, involving the use of nine levers and twenty-seven knife-edges, the object being to gain so enormous a leverage (in some cases 24,000 to 1) that the stress is balanced by very small weights. Fig. 48 shows diagrammatically the Thomasset machine, the

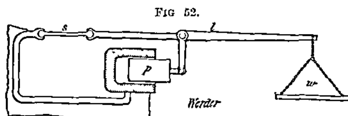




general arrangement of which is the same, but in which a manometric arrangement *d* is substituted for the

has been adopted very extensively in Germany. This differs from all the preceding machines in this, that both the weighing and straining apparatus are at one

Fig 52.



end of the specimen. Hence, the expensive parts of the machine being all at one end, arrangements can be made to take in specimens of almost any length, by prolonging the bed of the machine, without much extra expense. All the German Werder machines take in specimens in both tension and compression 30 feet in length, a result not obtained in any other type of testing machine except that at Watertown, and there only with greater difficulty, as the press must be movable. In the Werder machine the hydraulic press acts on the short arm of a single bent lever *l*. This lever is carried by the specimen, so that the other end of the specimen requires only a fixed abutment. By the action of the press the lever is kept horizontal, notwithstanding the deformation of the test bar. The Werder machine may be described as a machine in which the principal lever is supported on a moving fulcrum. The great advantage of having only a fixed abutment to provide for the back end of the specimen is obvious. Another advantage in this machine is, that

the short arm of the lever can be reduced as much as one pleases without shortening the knife-edges. It will be shown presently that actual Werder machines for testing specimens up to 30 feet in length, and up to a load of 100 tons, have a short lever arm of 1 m.m., or $\frac{3}{16}$ inch in length only. Thus a leverage of 500 : 1 is easily obtained, and the loads to be handled are small. On the other hand, these very considerable and practical advantages are not obtained without some sacrifice. The sensitiveness of the main lever is so great that it must be adjusted by a spirit-level. Further, the ratio of the leverage must be determined by direct experiment with a control lever and weights.

48. *The Woolwich Dockyard* 100-*ton Machine*.—This machine, which embodies nearly every feature of importance in modern testing machines, is described and figured in the first edition of Barlow's 'Strength of Materials,' and must therefore have been constructed at a very early date.[1] It was intended chiefly for testing cables, but was used for ordinary testing also. Barlow describes its principle thus:—'The Admiralty have had constructed in Woolwich Dockyard for testing iron cables a machine in which the strain is brought on by hydrostatic pressure, but its amount estimated by a system of levers, balanced on knife-edges, which act quite independently of the strain there is on the machine, and exhibit sensibly a change of pressure of $\frac{1}{8}$ ton,

[1] *Treatise on the Strength of Timber and Iron* By P. Barlow, F R S. London, 1837, p 237.

edged bar fixed between these side beams rests on the top of a strong iron standard. At 0·6 inch only from the fulcrum knife-edge is the knife-edge supporting the shackle. The lever is prolonged backwards, and carries a counterweight for putting it in balance initially. A travelling jockey weight runs along the lever, which is virtually a steelyard, and so balances the strain in the specimen. A peculiar arrangement is adopted to take up the deformation and keep the lever horizontal. This is a wedge, sliding in guides, and driven by a screw and gearing. As this arrangement produces no shock, it is probably very meritorious, at least for light machines.

SINGLE-LEVER MACHINES

50. *The Werder* 100-*ton Testing Machine.*—In 1852 a testing machine was designed for the Railway Commission of Bavaria by Ludwig Werder, and constructed by Messrs. Klett & Co., of Nuremberg. Similar machines have been built for the Government testing laboratories at Berlin and Munich, for the Polytechnic Schools at Zurich and Vienna, and for several manufactories and railways. Probably it is not too much to say that by far the largest part of the original mechanical investigations carried out in the last fifteen years has been accomplished by the aid of Werder machines. In the hands especially of Dr. Bauschinger, of Munich, tests of materials have been made with this machine with a precision and accuracy never before attained.

The Werder machine is a horizontal testing machine with hydraulic press worked by pumps and single-lever weighing apparatus. By an ingenious arrangement the press and lever are kept on the same side of the specimen. All the complicated and expensive parts of the machine being thus brought to one side of the specimen, comparatively simple and inexpensive arrangements can be made for extending the machine to take in specimens of very great length. Usually the Werder machine is made to test specimens both in tension and compression up to 30 feet in length.

The general principle of the arrangement of this machine has already been indicated. Fig. 53 shows a sectional elevation of the more important working parts, and detailed drawings will be found in the treatises cited below.[1] R is the hydraulic press ram, which acts against a knife-edge on what is really a bent lever L_1. The crosshead C_1, which holds one of the shackles S_1, is connected by the long bolts *t*, *t* with a crosshead carrying the other knife-edges which support the lever. If the specimen stretches, C_1 moves to the right, and the lever falls; if the press ram is then moved to the right the lever is again lifted. The back crosshead C_2, which holds the other shackle S_2, slides on a cast-iron railway behind the machine. It is spaced at any distance from the fixed frame of the machine by the loose distance pieces *d*, *d*.

[1] *Mittheilungen a. d. mechanisch-technischen Laboratorium in München*, Heft 1 & 3. *Maschine zum Prüfen der Festigkeit der Materialien und Instrumente zum Messen der Gestaltsveränderung der Probekörper.* München, 1882. Also Lebasteur, *Les Métaux.*

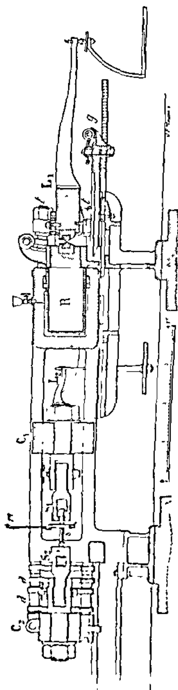


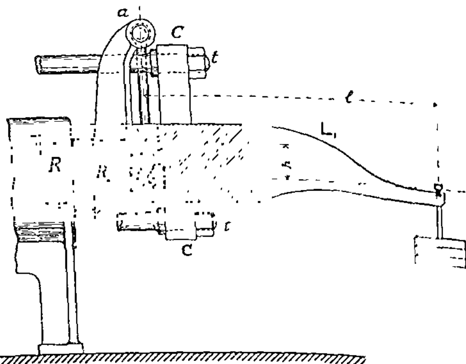
Fig 53.

At *s* is a tension test-bar, and *m* is Bauschinger's mirror arrangement for measuring extensions. In testing, weights are placed on the scale platform of the lever L_{11}, and then by the pumps the ram R is moved out till the lever is in balance.

To obtain a high ratio of leverage, so that the weights to be handled may be small, the short arm of the lever L_1 is reduced to the extraordinarily small distance of 4 mm. or $\frac{3}{16}$ inch. The lever is of such a length that the leverage is 500 : 1. Of course the short-arm length of the lever cannot be directly measured with accuracy enough to determine the leverage of the machine. Hence a second lever (control lever) L_2 is provided, acting on the crosshead C_1. This lever has a ratio of 10 : 1, and its arms can be accurately measured.

By putting weights acting on L_2 in balance with weights acting on L_1 the leverage of the principal lever L_1 is determined. With so small a fulcrum distance as $\frac{3}{16}$ inch the width of the knife-edges is a quantity comparable with the short arm-length of the lever. It is necessary, therefore, that the lever L_1 should have an

FIG 51



extremely small range of motion. This is secured by placing a spirit-level on the lever g is hand-gear for returning the press ram after a test.

The arrangement of the hydraulic press and lever will be better understood from the diagrammatic sketch, Fig. 51. Here R_1 is the press cylinder cast in one with

the frame of the machine, and R_2 is the press ram. The press ram, cased in gun-metal, is 12 inches diameter. The hand-pumps for working the press have rams of 1·2 and 0·4 inch diameter. The ram R_2 carries a horn *a*, with cross-shaft, from which the great lever L_1 is suspended by links, and also the crosshead C connected with the front shackle. The back part of the lever L_1 is a large U-shaped casting, partly surrounding the press, so that the centre of gravity is near the knife-edges. It carries a scale platform and adjusting weight. The pair of crossheads C pass through the lever, and are connected each by two longitudinal tie-rods *t* to the shackle crosshead. The press ram carries in front a hard steel prism $14\frac{1}{2}$ inches long, against which one knife-edge on the lever acts. The crossheads C each carry a prism $7\frac{5}{8}$ inches long, against which the other knife-edges act (shown dotted). The distance between the upper and lower knife-edges, reduced to $\frac{3}{16}$ inch in the actual machine, is the short-arm length *h* of the bent lever, the long arm being *l*.

Fig. 53 shows the arrangement of the machine for testing bars in tension. For crushing cubes and short specimens the space between C_1 and the back of the press is utilised, proper seatings being introduced. Longer specimens can be crushed between C_1 and C_2, the tie-bars *t*, *t* being then extended to the cross-head C_2. Convenient arrangements for transverse testing and for torsion are also easily fixed.

51. *Single-lever Testing Machine of Messrs. Buckton*

and Co., of Leeds.—This machine was described at the Leeds meeting of the Institution of Mechanical Engineers.[1] The machines then constructed were 50-ton machines for testing ordinary short commercial test-bars. It appeared to the author in 1883 that a larger machine, capable of taking in moderately long specimens, could be constructed on the same general plan. In correspondence with Mr. Hartley Wicksteed, plans were made for a 100-ton machine, which would take specimens 6 feet long. Two very satisfactory machines were built of this size, under the author's direction, for the engineering laboratories at Cooper's Hill and at the Central Institute of the Guilds of London. Other machines of the same power have since been made. Considered as an instrument of general scientific research, the Buckton machine, even on the larger scale, is inferior to the Werder machine. But it is more handy for ordinary testing, and probably it is more easily kept in trustworthy adjustment.

Fig. 55 shows the general arrangement of the 50-ton Buckton machine. H is a rigid cast-iron standard bolted to the foundations, and having at top a horn projecting back to carry the principal knife-edge or fulcrum of the lever. The great lever L, L, with its jockey-weight W, forms the weighing apparatus, and the hydraulic ram F, F takes up the deformation of the specimen. A tension specimen is shown at S, between the friction-grip shackles A, B. The knife-edges of the

[1] *Proc Inst of Mech Eng*, 1882

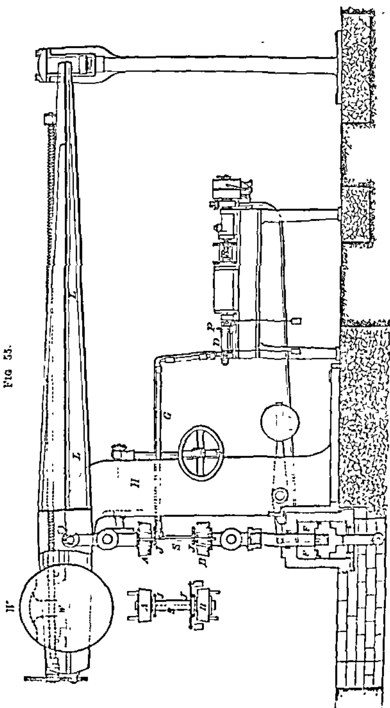


FIG 53.

lever L, L are 3 inches apart, one resting on the standard H, the other supporting the shackle A. To support the knife-edges and prevent flexure, they are gripped by rigid castings bolted between the side plates of the lever. The hydraulic press F has a stroke of 6 inches to take up elongation and slip of the test-bar in the grips. The press is worked by means of a 'quiet compressor.' This is a press with a ram driven by a pair of screws, which again are driven by gearing and belting. This secondary press, which is a substitute for the pumps ordinarily employed, forces water into the main press F quietly and without shock, and works very satisfactorily indeed. More power, however, is required than with pumps. The press is so used that the lever is kept 'in balance'—that is, floating freely between the stops which limit its motion. The jockey-weight weighs exactly one ton, and can be moved along the lever by a screw driven at will, either by belting or by the hand-wheel in front of the standard. Before a test the jockey-weight is run back till the lever is in balance with the test-bar free. A vernier, attached to the jockey-weight, is set to zero on a scale running along the lever. Then the specimen is fixed, and the jockey-weight moved out along the lever, while the press is used to keep the lever horizontal. Each 3 inches of movement of the jockey-weight adds a ton to the load on the specimen, and the vernier easily reads on the scale to $\frac{1}{100}$ ton.

52. 100-*ton Testing Machine of Messrs. Buckton and Co.*—The photographic frontispiece shows a general

view of the engineering laboratory at the Central Institute, with the 100-ton testing machine. Plate II. is a general elevation of the same machine. F, F is the main standard of such a height that moderately long specimens can be tested. To the foot of this standard is bolted the principal hydraulic press R, the ram of which acts downwards on a crosshead c_1, connected by adjusting side screws to an upper crosshead c_2, to which the lower specimen shackle S_2 is attached. There is worm-gearing to the side screws to adjust the length between the shackles S_1, S_2. The press-ram is kept home by the balance-weight B, attached to it by spring shackles. To work the press there is a second press or compressor C, the ram of which is driven by the twin screws s_2 and gearing g_2. The crossed belts b_2 and fast-and-loose pulleys behind the standard drive the compressor ram in or out, and so force water into or allow it to flow back from the main press R. r_2 is a hand-lever to the fork actuating the belts b_2, which drive the compressor.

The great main lever L, of wrought-iron side-plates, rests on the top of the standard F, F by means of a knife-edge, and a second knife-edge behind this supports the upper shackle S_1. These knife-edges are 20 inches long, and are formed of hardened steel ground into a rectangular groove in steel bars 4 inches in diameter. These bars are further supported by castings bolted to the side-plates. The distance between the knife-edges is 4 inches. The free end of the lever plays in a space

S

a

o

L

P

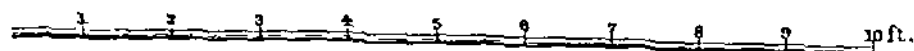
W

S2

100 Ton Testing Machine.

Messrs. Buckton & Co. Leeds.

Scale.



in the supporting pillar P. J is the jockey-weight, weighing one ton, and straddling the lever so that its centre of gravity is as nearly as possible on the plane through the knife-edges. This runs on four rollers on rails fixed each side of the lever, and is moved by the long screw *s*, *s*. The jockey-weight can be put in motion either by the crossed belts b_1 connected with the reversing handle r_1, or by the hand-wheel *h* and countershaft *k*, if very slow motion or fine adjustment is required. Along the lever is the graduated scale *a*, *a*, and a vernier *v* on the jockey-weight indicates the position of the jockey-weight. Initially the lever is put in balance, and the vernier set to read zero on the scale. Then each 4 inches the jockey-weight moves adds a ton of stress on the specimen. The scale is 200 inches long, so that with the jockey-weight at the end of the lever a stress of 50 tons is measured. For greater stresses the jockey-weight is run back to zero, and the 25-cwt. load W is attached to the lever by a screw coupling. As this hangs at a leverage of 40, it balances a stress of 50 tons. The jockey-weight is then run out again. The vernier easily reads to $\frac{1}{200}$ ton. Although the arrangement of a double weight may seem cumbrous, it is not so in practice, and the author prefers it to the plan of making the jockey-weight 2 tons. In three-fourths of ordinary testing, or more, the stresses do not exceed 50 tons, and the coupling up of the extra load is very easily managed.

The tension shackles S_1, S_2 are shown in place, and will

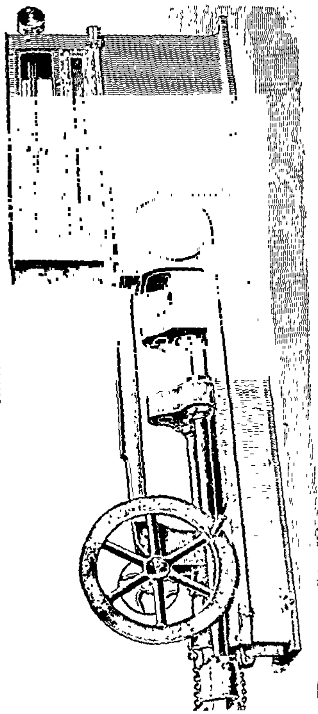


FIG. 56

tion, which requires no bolting down. It is capable of testing all kinds of materials in tension, compression, and bending ; by a special arrangement it may also be used for torsion. The testing stress is obtained by an hydraulic cylinder and ram $6\frac{3}{4}$ inches in diameter. The cylinder is of forged steel, and is intended to carry a working pressure of about three tons per square inch. The pressure is obtained by a small double cylinder pump, driven by cranks, and is provided with a fly-wheel, pulleys, and handle for hand or power driving. The plungers are made on the compound principle, one small one working inside an annular plunger. When it is required to pump rapidly at low pressures both of them are coupled together, forming one large plunger ; but for high pressures the inner one only is used : then the speed has to be sacrificed for pressure. This arrangement permits two men to pump up to the full power of the machine, viz. 100 tons. The pressure on the ram is transmitted to a substantial cast-steel cross-head by means of two steel ties, 3 inches in diameter, running along either side of the machine. These ties are screwed at the ends to allow of the crosshead being adjusted for various lengths of specimens.

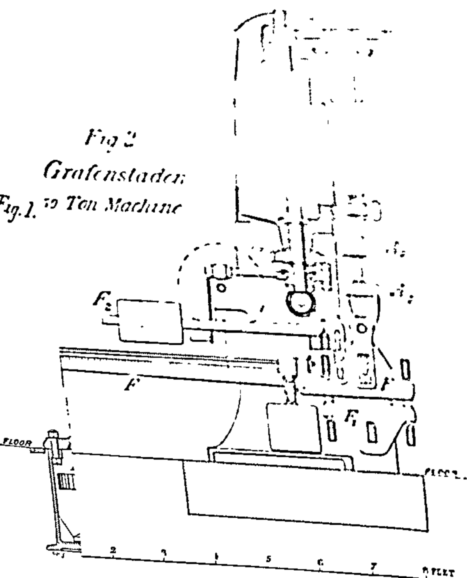
The gripping-jaws for holding the specimens are turned on the outside and then fitted into a circular hole. This arrangement insures the perfect gripping of bars or plates having tapered cross-sections. In ordinary rigid jaws the thick side is gripped first, and consequently a tearing action is produced instead of a

fair and uniform pull. The other end of the bar is similarly held by a second crosshead which is attached to a set of three levers, and a steelyard provided with a travelling weight, the position of which indicates the load on the specimen under test. The leverage obtained is 15,000 to 1, so that a very small travelling weight can be used, viz. 4 lbs.; when greater loads are required, other weights of 3 lbs. each are hung on the end of the steelyard.

All the levers and steelyard are arranged in a case to protect them from dust and injury. The handle for adjusting the traversing weight is placed outside of the case, so that it never need be opened except for cleaning; the steelyard is visible through a glass door.

By means of very simple attachments this machine may be adapted for testing specimens in compression or bending. The hydraulic ram is provided with a chain and weight to bring it back to its original position after the fracture of the specimen. All the knife-edges on the levers are of hardened steel, and specially arranged to prevent warping in hardening. This machine is very conveniently arranged for getting at the specimens when under test; it is also very compact.

55. *Olsen Compound-lever 100-ton Testing Machine* (Plate III., Fig. 1).—This is of the type largely adopted in America, the mechanism being in principle the same as that of a platform weighing machine. Four columns on the platform E carry the steel plate B, to which one end of the specimen is attached. Four straining screws


Fig 2
Grafenstaden
Fig. 1. 70 Ton Machine
F_2
F
F_1
FLOOR
2
3
4
5
6
7
8 FEET

MACHINES.

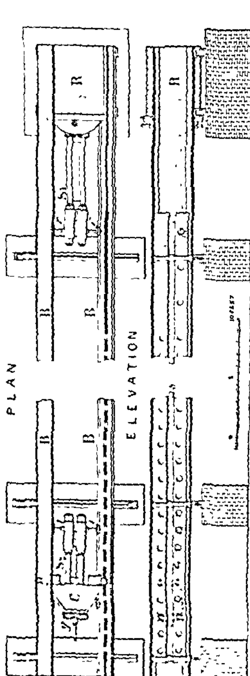
carry the plate C, to which the other end of the specimen is attached. The columns supporting B rest on the lever system F, F. The straining screws carry the large driving-nuts H, which are put into action by the gearing below the levers. The nuts abut against the frame through roller bearings, to diminish friction.

The platform E rests on three main levers, acting as a single lever. Beyond the platform the three levers act through a stirrup on the second lever F_2, and this again is connected with the third lever or graduated steelyard F_3. A small poise or jockey-weight gives the measurement of stresses from 0 to 5,000 lbs.; a larger poise, stresses from 5,000 to 100,000 lbs.; and an additional weight on the end of the lever adds 100,000 lbs. The screws and driving-nuts take the place of the hydraulic press used in other machines. A crossed belt on the pulley T, and open belt on the pulley U, drive the gearing. A friction clutch engages either pulley with the driving-shaft. There is also a slow motion by friction-gear V.

SIMPLE HYDRAULIC PRESS MACHINE.

56. 600-*ton Testing Machine of the Union Bridge Company, at Athens, Pa.*—This machine was constructed with the object primarily of testing the full-size eye-bars which are so largely used in American bridge construction.

Two horizontal riveted girders B, B (Fig. 57) 60 feet in length, supported by cross-girders on five



masonry piers, form the frame of the machine. At one end of the frame is a large hydraulic press cylinder R, with a freely moving piston. This has four piston-rods, to which is attached a crosshead carrying shackles S_1 for one end of the test-bar. There is a movable tail-piece C, which can be attached at any point in the length of the frame, which carries a similar crosshead and shackle S_2 for the other end of the test-bar. The crossheads are carried on accurate wheels *r*, *r*, running on a track fixed to the

lower flange of the frame girders. The tail-piece having been fixed to the girders at a suitable distance from the hydraulic press, the specimen is introduced. Then pressure is applied to the piston of the press, and increased till the specimen breaks. The pressure on the piston is measured by a Shaw mercury column and by a spring pressure-gauge. The load on the specimen is taken to be equal to the pressure on the press cylinder. It will be seen that in this very large and important machine the principle of construction is simple, the lever weighing apparatus being dispensed with.

The hydraulic press cylinder R is of cast steel, 4 feet $3\frac{3}{4}$ inches bore and 6 feet $0\frac{1}{2}$ inch long. It has an area of 2,039 inches, and an effective stroke of 4 feet 11 inches. The maximum water-pressure for which provision has been made is 600 lbs. per square inch. The cylinder is secured to the girders by bolts, and its back end is left open, so that the piston can be seen.

The main girders B, B are of wrought iron, 60 feet long, 3 feet 6 inches high, built of plates and angle bars, rolled in one length. Holes, $6\frac{1}{2}$ inches diameter and 18 inches apart, are bored through the web for the bolts of the tail-block. Along this part of the web it is $2\frac{1}{2}$ inches thick.

The tail-block C is a steel casting, which may be attached to the main girders by two pins each side, fitting the $6\frac{1}{2}$-inch holes. Geared steel nuts *g* give a

further adjustment of the distance of the shackle from the tail-block.

To provide for recoil between the shackle and tail-block there is a rod attached to the shackle passing through a friction-clamp on the tail-block. The eye-bars are attached to the shackles by a $7\frac{1}{2}$-inch pin in an elongated hole $7\frac{1}{2} \times 9$ in the shackle. This permits the specimen to recoil independently of the shackle. When smaller pins must be used collars reduce the size of the pin-hole.

The shackle attached to the hydraulic press piston is similar. The piston has a gland and hemp packing, and the piston-rods also pass through stuffing-boxes. The piston-gland is tightened till the leakage, with maximum pressure, is reduced to a thin film of water discharging uniformly round the piston. After a specimen is broken a discharge-cock is opened to a tank 4 feet 6 inches below the cylinder. The small vacuum thus formed, equivalent to $1\frac{1}{2}$ lbs. per square inch on the piston, is found sufficient to move it home. Hence it has been assumed that 3,000 lbs. represents the maximum allowance to be made for the friction of the hydraulic press. For practical purposes this allowance is disregarded.

The pressure is obtained by a pump with three single-acting plungers, $2\frac{1}{4}$ inches in diameter and 10 inches stroke, working at slow speed. An engine with two cylinders, 8 inches diameter and 8 inches stroke, works the pumps.

With a maximum load the stresses on the parts of the machine are as follows :—

Main girders . . .	7,100 lbs. per sq. in.	compression	
Steel castings . .	15,000 ,,	,,	,,
,, . . .	13,000 ,,	,,	tension
Connecting rods . .	15,000 ,,	,,	,,
Bolts . . .	12,000 ,,	,,	shear.

All these stresses are for the net effective sections, and the margin of safety appears to have proved sufficient under the shock of sudden release of load. Bars varying from 5 to 18 square inches section have been broken in the machine. It is intended to construct compression apparatus for this machine.

The machine was designed by Mr. Charles Kellogg. The idea involved in its design is thus stated by Mr. Macdonald :—'It is not contended that this is an instrument of precision, or that in sensitiveness or accuracy it is the equal of the testing machine at Watertown Arsenal. Mr. Kellogg would be the last person to invite comparison in that respect with the superb invention of Mr. A. Emery. What he has accomplished has been the construction of a machine at moderate cost, which will test to destruction full-sized sections as they are required for structural purposes, with rapidity and reasonable accuracy.'

The particulars and description of this machine have been taken from a paper read before the American Society of Civil Engineers by Mr. Charles Macdonald, M.Am.Soc.C.E.[1]

[1] *The Railroad and Engineering Journal*, vol lxi p 71.

MANOMETER MACHINES.

57. *The Thomasset Machine*[1] (Fig. 48).—M. H. Thomasset, of Paris, constructed, apparently about 1872, a machine differing in its mode of action from previous machines in two ways. (1) To force water into the hydraulic press a 'quiet compressor' ('compresseur sterhydraulique'), like that used in oil presses, is employed instead of pumps. It has the advantage of convenience, and of preventing the pulsatory action produced by pumps. However, it requires more power to drive it. (2) In the weighing apparatus the pressure of a liquid column acting on a large diaphragm, which forms a virtually frictionless piston, is employed to balance the stress on the specimen. This has the advantage of convenience, cumbrous weights being dispensed with. It has the further very important advantages that the inertia of the weighing apparatus becomes very small, and that the load adjusts itself perfectly automatically to the stress. The slightest variations of stress are indicated by the rise of the liquid column, which balances the stress independently of any manipulation by the operator. Apart from the question of the success of M. Thomasset in overcoming the difficulties of a new problem, his machine has very great merit from a theoretical point of view. Other makers have proceeded on the same lines, and probably the Thomasset machine

[1] Lebasteur, *Les Métaux*, p. 52.

is in some degree the parent of the great machine at Watertown.

One shackle of the machine being attached to the ram of a press, the other is attached to the short arm of a knee lever. The longer arm presses on the centre of a diaphragm covering a circular cistern of mercury, or of water communicating with the cistern of a mercury manometer. The diaphragm is a vulcanised rubber sheet fixed round its edge by a ring, and receiving the load from the lever on a loose circular metal plate only slightly less in diameter than the cistern.

Let Ω be the area of the circular diaphragm in sq. centimeters; P the stress on the specimen in kilograms; n the leverage of the bent lever. The total pressure on the diaphragm is P/n kilograms, and the pressure in the cistern is $P/\Omega\, n$ kilograms per sq. c.m. But if h is the height in c.m. of the mercury column in the manometer, measured from the level of the cistern (or, strictly, from the point where the mercury stands with no stress on the specimen),—

$$\frac{h}{76} = \frac{P}{\Omega\, n}.$$

If $\Omega = 5{,}000$ sq. c.m. (about 2·6 feet) in diameter; $n = 5$; then a column of mercury $1\frac{1}{2}$ meters (5 feet) high will balance 50,000 kilograms (50 tons) of stress. As the section of the mercury column is only $\frac{1}{5000}$ of the area of the diaphragm, the whole movement of the diaphragm for a load of 50 tons is only half a millimeter (0·02 inch).

58. *The Maillard Testing Machine* (Fig. 51).—A very interesting machine,[1] based on the same principles as the Thomasset machine, was designed by Colonel Maillard for use in the French arsenals, and one of these machines is now in daily use at Woolwich. Broadly speaking, it is a Thomasset machine in which the lever is got rid of, and the pull taken directly on the diaphragm. This involves an enlargement of the size of the diaphragm, and some other changes. The machine as hitherto constructed is only suitable for short specimens, and is only arranged for tension.

In this machine the specimen is held horizontally between shackles, one attached to the ram of an hydraulic press, the other to a crosshead which pulls on a diaphragm in a cistern containing fluid. This short cylindrical cistern has the same axis as the hydraulic press, and necessarily the diaphragm which receives the pressure is on the side furthest from the test-bar, so that the crosshead is forked to surround the cistern. The diaphragm is of caoutchouc, protected by a metal plate. The cistern communicates by a pipe with a Galy-Cazalet manometer, or a mercury manometer. The cistern is carried on trunnions upon a carriage sliding horizontally. By means of a screw and hand-wheel the position of this carriage can be adjusted to suit different lengths of specimen.

The stress in the test-bar, transmitted through the shackle and crosshead to the plate or piston at the

[1] Lebasteur, p. 53.

back of the cistern, is exactly balanced by the fluid pressure. The diaphragm moves at most only a small fraction of a millimeter, so that the friction and bending resistance of the diaphragm is quite negligable. Consequently, if the graduation of the manometer is correct, the stress is determined with great accuracy. If P is the stress on the bar, h the rise of the mercury column in the manometer above the zero at which it stands when no stress is applied, δ the density of the mercury, S the area of the diaphragm, s_1 and s_2 the large and small areas of the manometric piston,—

$$P = h \delta S \frac{s_1}{s_2}.$$

To eliminate errors due to uncertainty as to the areas of the diaphragms, to capillarity, and so on, the manometer is graduated by experiment. The cistern is removed from the machine, laid horizontally, and loaded with standard weights.

In a good manometer the tube must be at least 3 centimeters in diameter ($1\frac{1}{4}$ inches); with a smaller column, drops of mercury remain attached to the tube when the column falls. The manometric piston in the manometer used is so arranged that the centimeter rise of column corresponds to the kilogram per square centimeter on the smaller piston, and consequently on the diaphragm of the main cistern of the testing machine. Hence if n is the rise of column in centimeters, and S the area of diaphragm in centimeters,—

$$P = n S.$$

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[1] Lebasteur, p. 63.

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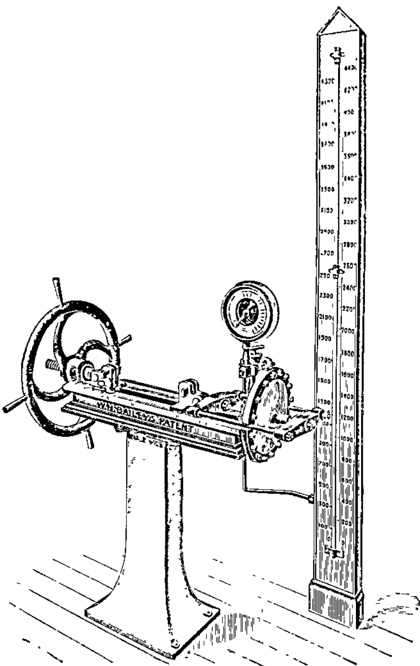
In the machine at the Ruelle Foundry the diameter of the large diaphragm is 9 feet.

59. *Wire-testing Machine of Messrs. W. H. Bailey and Co., of Salford.*—Fig 58 shows a very nicely arranged small tension machine, on the same principle as Col. Maillard's. One end of the specimen is held in friction-grips in a shackle attached to a screw and hand-wheel, which takes up the elongation. The other shackle is attached to crossheads and links, which surround the diaphragm chamber, and apply the load on the back of the diaphragm. The pressure in the diaphragm chamber is transmitted to a pressure-gauge and to a mercury column, either of which can be used. There is a valve on the pipe allowing flow towards the pressure-gauge or mercury column, but preventing back flow. This holds the gauge at the maximum pressure, and prevents injury when the specimen breaks and the load is suddenly removed. A small hand-wheel opens this valve and lets off the pressure slowly. The machine will give a tension of 4,500 lbs.

EMERY MACHINES.

60. *The 450-ton Emery Testing Machine at Watertown Arsenal, U.S.A.*—In 1872 a committee of American engineers was formed to urge on the Government of the United States the importance of a thorough and complete series of tests of American iron and steel. Subsequently, by direction of the Government, a Board was constituted for the purpose of carrying out tests

Fig. 58.



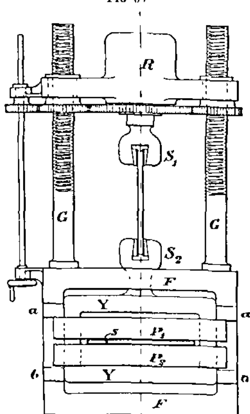
The Emery machines differ essentially in principle from any others. They are really compound lever machines, with an hydraulic press acting on one end of the specimen, and a lever weighing apparatus on the other end. But their greatest peculiarity is that a kind of hydraulic lever is introduced between the specimen and the weighing apparatus. The pull of the specimen is taken on an 'hydraulic support,' the action of which is like that of the diaphragm in the Maillard machine. The fluid pressure in the hydraulic support, which is exactly proportional to the stress on the test-bar, is transmitted through a very small pipe to act on a frictionless diaphragm of comparatively small size, and it is the pressure on this diaphragm only which has to be balanced by the lever weighing apparatus. The weighing apparatus can therefore be made of small size, and of the utmost refinement and accuracy.

In the 75-ton machine the ratio of areas of the diaphragms is 20 : 1, so that the lever weighing apparatus has to balance 3·75 tons only with the full load. There are three levers with ratios of 1 : 20, 1 : 20, and 1 : 40, so that the resultant leverage is 320,000 to 1.

The action of the Emery machine may, perhaps, be made clear by the diagrammatic sketch of a vertical machine (*Fig. 59*). *A tension specimen is shown* between the shackles S_1, S_2. The upper shackle is held by the ram of the hydraulic press, which can be adjusted on the guide-screws G, G. These screws are fixed on the frame F, F of the machine. The lower shackle is

attached to a yoke or frame Y, Y, which transmits the load to the hydraulic support. At *s* is a thin circular brass sac, filled with alcohol and glycerine, supported over all its area, except a ring $\frac{1}{8}$ inch wide at its circumference, by the strong and rigid crossheads P_1, P_2. When the machine is acting as shown in tension the yoke transmits the load to the crosshead P_2, and thence through the sac *s* to P_1, which rests against the stops *a*, *a* on the frame. For compression the yoke presses downwards on P_1, through *s* to P_2, and P_2 then rests on the stops *b*, *b*. The whole play of the crossheads between the stops *a* and *b* is only $\frac{1}{5000}$ inch.

Fig 59



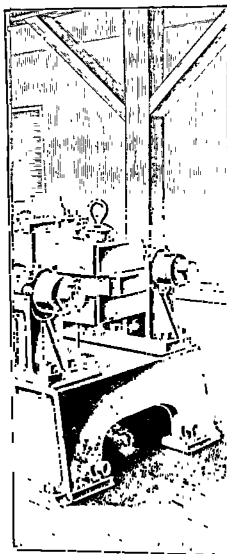
The movement of the yoke and compression of the hydraulic support is determined by the amount of motion permitted in the lever weighing apparatus. With the 75-ton machine, when the indicating lever moves 4 inches (2 inches above or below mean position)

hydraulic press 1569 (Fig. 1), with its shackle or holder 1475. At the left is the hydraulic support, the cross-heads of which are seen at 1455, 1456, with the other shackle 1475. The frame at the left end is connected with the press by the guide-screws 1450. The hydraulic press is carried on a four-wheel truck, and can be set at any distance from the hydraulic support, to suit different lengths of test-bar. The guide-screws are 48 feet long and 8½ inches diameter, and are driven by the geared nuts 1569 and the gearing at the extreme right of the figure. When the gearing is not acting the press is locked to the screws. The press has a 20-inch ram, with a piston-rod 10 inches diameter. The press is worked by accumulators, and acts in both directions, according as tension or compression is required.

In each of the test-bar holders there are two 14-inch hydraulic presses, which grip the specimen with a force of 500 tons.

The space for the ends of the specimen is 10 inches deep in the middle and 5 inches at the sides, and it is 30 inches wide.

The hydraulic support rests on a longitudinal slide, its motion being controlled by powerful buffer-springs, which absorb the recoil when the specimen breaks. In ordinary conditions the buffer-springs merely hold the hydraulic support in its middle position. When a specimen breaks, the press and hydraulic support recoil in opposite directions, the forces developed being opposed by the guide-screws. But as the recoiling forces



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manometer. This seems to contain the essentials of a perfect torsion machine, but the shackle arrangements for holding torsion specimens do not seem as yet to have been fully thought out. Prof. Kennedy gives details of a small torsional machine.[1]

Thurston's autographic torsional machine will be described in a later chapter.[2]

62. *Machines for Transverse or Cross-breaking Tests.*—Shackles for cross-breaking are provided with most large testing machines, and will be described in the next chapter. For transverse tests of cast iron small special testing machines are useful. Bars of cast iron $3\frac{1}{2}$ feet × 2 inches × 1 inch, laid on supports 3 feet apart, with the deeper side vertical, break with from 25 to 40 cwts. placed at the centre, so that the loads to be dealt with in tests of this kind are not very great.

FIG 61

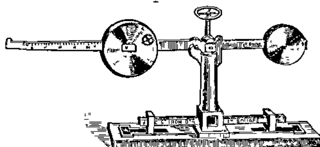


Fig. 61 shows a small machine, made by Messrs. Tangye Brothers, for tests of this kind. The bar rests on knife-edges on the base-plate, and is loaded at the

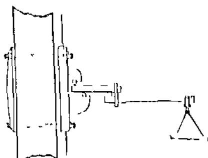
[1] 'Engineering Laboratories' *Proc. Inst. Civil Engineers*, vol lxxxviii.
[2] First described in *Proc. Am Soc. of Civil Engineers*, 1874, p 350

centre by a lever and jockey weight. Somewhat similar machines are made by Messrs. W. H. Bailey & Co., and probably by other engineers.

M. Kuhlmann has introduced a machine of rather more elaborate construction for breaking cylindrical test-bars $\frac{3}{4}$ inch in diameter and 8 inches in length. It is suggested that small test-bars of this kind can be more easily and accurately cast, can be cast vertically, and are, if desired, easily turned in the lathe, so as to be quite accurate in form. The pattern for casting them is a polished metal bar. There is an arrangement in the machine for indicating deflections.

Another convenient arrangement, known as the 'Balance Monge,' is in use in some gun factories. It consists of a bracket (Fig. 62), fixed to a wall, having two opposed knife-edges. By a bridle and block a scale-platform is attached to the bar.

Fig. 62.



63. *The Bending and Temper Test.*—A very convenient practical test of the ductility of a material is to bend a strip about $1\frac{1}{2}$ inch wide over a corner of small radius, and observe the angle at which it cracks on the extended side. Sometimes the test is made on strips in the condition in which the material is received. In the case of steel, strips are heated to cherry red and plunged

in water of a temperature of 80° before bending. This shows whether the steel tempers or hardens by sudden cooling. Sometimes the strips are simply sheared strips. At other times the edges of the strips are planed or the strips annealed, and they then bend to greater angles before cracking.

The roughest plan of bending is to put the strip of plate over a V-block, and bend it by blows of a heavy swage ; the bending is continued by light endway blows of a steam hammer. A press for bending angle iron may be used in a somewhat similar way, the pressure being applied first transversely, then endways. In experiments by Prof Kennedy,[1] bars 1¼ inch square were supported on knife-edges 6 inches apart. A load was applied steadily on a central bearing-piece of 1¾ inch radius. When the angle reached 90° the bearing-piece was reduced to ⅞ inch radius. In experiments for the Board of Trade, strips were placed on supports 10 inches apart and bent by hydraulic pressure to an angle of 90° by a ram with a rounded end of 2 inches radius. The bending was then continued till the strip cracked or the angle reached 180° by quiet pressure applied at the ends, in the testing machine. Mr. Strohmeyer[2] clamped pieces between a steam hammer and its anvil, hammering the projecting end till the strip was bent through an angle of 45°. It was then reversed and

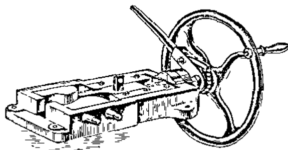
[1] 'The Use of Steel Castings,' Parker. *Journal of the Iron and Steel Institute.*

[2] 'The Working of Steel,' Strohmeyer. *Proc. Inst. of Civil Engineers*, vol. lxxxiv

bent in the opposite direction, and the bendings continued till fracture occurred. The number of bendings is taken as a measure of the ductility of the material. To ensure accurate bending to a given angle, an anvil mould, with a radius of curvature of $1\frac{3}{4}$ inch, was used below the test piece.

A lever apparatus for quietly bending strips of plate is described in the work cited below.[1] Fig. 63 shows a small apparatus of this kind introduced by Mr. A.

Fig 63



H. Kuhlmann. It has a screw worked by a handwheel or by a ratchet lever. The piece to be tested is bent in the middle, and the angle measured subsequently. It will bend strips 2 inches wide and $\frac{3}{4}$ inch thick.

64. *Testing Pipes.*—As water mains of cast iron are ordered in very large quantities, special arrangements for testing them before delivery are generally adopted.

The general quality of the metal used is determined by testing sample bars cast once or twice a day from the same metal as the pipes. These are most commonly bars 2 ins. × 1 inch × 40 ins, which are broken trans-

[1] *Die Eigenschaften von Eisen und Stahl* Wiesbaden, 1880

versely on supports 36 inches apart. In some cases, however, a tension test is made; and this is no doubt the more rational proceeding.

Next to this, the regularity of form of the pipes is tested. The thickness is tested by callipering, long callipers of special construction being used. A variation of $\frac{1}{8}$ inch in thickness is the most generally allowed. A pipe with $\frac{1}{4}$ inch variation in thickness should be rejected unless the working pressure is light. In rolling the pipes they usually come to rest with a thin side uppermost, and this is some guide in determining the thickness. Ordinary callipers are 18 inches in length; special callipers have been made up to 6 feet in length, but these, from their springiness, require a good deal of care and skill in use. Deviation in weight is also noted. Usually pipes with a deviation of 2 to 5 per cent. are rejected. Socket and spigot gauges for the inside of the socket and outside of the spigot are also used. A disc with a long handle passed through the pipe is used to show deviations from cylindrical form. The disc is usually $\frac{1}{4}$ inch less in diameter than the nominal bore of the pipe. This disc should pass fairly through the pipe while held square.

The most important test, however, is the hydraulic pressure test. The testing machine consists of two standards on a frame, carrying discs which are pressed against the ends of the pipe. One disc is fixed, the other movable. A grummet, consisting of an iron ring served with tarred rope or yarn, is inserted between the

discs and pipe to make a joint. The movable head is forced up by a screw, which exerts considerable pressure. Water is then run in till the pipe is full from a cistern, the air escaping by an air-vent. The air-vent and supply-pipe are then closed, and a pressure produced by a small force-pump. A weighted valve and a pressure-gauge show when the pressure required for testing is attained. For pipes of 30 inches or more in diameter 4 to 5 lengths can be tested per hour. The pressure prescribed is usually double the working pressure. While under pressure the pipes are struck hard with a hammer of 5 to 7 lbs. Leakage through the pipe is indicated by the fall of pressure shown by the gauge. If proved before coating with tar or asphalte defects are more easily seen.

64 *a*. *Calibration of a Testing Machine.*—Experimental verification of the accuracy and sensitiveness of a testing machine is absolutely necessary, both in the first instance and at intervals afterwards. It will be sufficient to describe the process of verification adopted for the 100-ton Buckton testing machine. The stress in this machine is weighed by a jockey weight, and the first point to verify is that this jockey weight is exactly 1 ton. The jockey weight was adjusted at the Standards Office, and certified by the inspector. It is not difficult to verify this weight from time to time by lifting it, with one of the convenient steelyard weighing machines interposed between the crane-hook and weight.

Adjustment to Zero of Scale.—The adjustment is easily effected, and is necessary after any change of the shackles used. The jockey weight is run back till the lever rests in absolute equilibrium midway between the stops. The vernier attached to the jockey weight is then set to zero on the scale.

Verification of the Jockey Weight by the use of the Lever.—A very simple test of the accuracy of the jockey weight is made in this way. A uniformly graduated scale runs along the lever. Division 5 coincides with the principal knife-edge on which the lever rests, and at division 45 a subsidiary knife-edge has been fixed. Bring the lever to balance, and set the vernier to zero. Then run back the jockey weight to − 1 on the scale. A weight of 56 lbs., hung at division 45, or forty divisions from the fulcrum, ought to be in balance with the jockey weight moved one division back. If it is not, the jockey weight is not a ton. This simple test, which can be made in ten minutes, is sufficient at any time to check the accuracy of the jockey weight to about 12 lbs.

Verification of the Agreement of the Scale Divisions with the Short-arm Length of the Lever.—The fulcrum distance in this machine is 4 inches, and the unit of the scale must be 4 inches also. The agreement of the scale unit with the short-arm length is best determined by weighing. For this purpose a standard 1-ton weight, made of a suitable form, is hung from the shackle of the machine. The lever is balanced, and the vernier

set to zero. The ton weight is then hung in the shackle, and balanced by the jockey weight. The vernier ought then to read 1 ton on the scale. If it does not, the fulcrum distance must be altered, as it is inconvenient to alter the scale. Perhaps it is still more accurate to balance 56 lbs. at a leverage of 40 by the ton weight in the shackle without moving the jockey weight.

Test of Sensitiveness.—In this machine the lever and jockey weight, with the parts attached to them, weigh altogether about 5 tons, and this is therefore the *minimum weight on the knife-edge. With this weight* resting on the knife-edge there is a perceptible movement of the lever when $\frac{1}{2}$ lb. is placed on the shackle, and a return if the weight is removed. If the friction of the knife-edge is assumed to be proportional to the load, the error in 100 tons of stress would only be $10\frac{1}{2}$ lbs.

Probably a greater sensitiveness than this could be obtained if necessary. The knife-edge of this machine is of the exceptionally great length of 22 inches. Any initial or induced flexure virtually broadens the knife-edge and reduces the sensitiveness. Hence a very long knife-edge, though more durable, is likely to be less sensitive than a shorter one.

Test of Neutrality of the Lever.—The centre of gravity of the lever and jockey weight should be on the line passing through the knife-edges. If it is not so, the leverage alters, either decreasing or increasing as the inclination of the lever alters. The author has tested

T/ω is the *apparent tenacity*, which may be less than the real tenacity to almost any extent.

(1) The stress on the cross section will cease to be uniform if the resultant of the load P (Fig. 64, B), does not pass through the centre of figure. The stress is then a varying stress, varying uniformly so long as the elastic limit is not passed, and according to some other law if it is passed. The specimen tears from the edge where the stress is greatest. At C the load is also eccentric, and this indicates how non-uniformity of stress may be produced by unhomogeneousness of the material itself. A patch of material of different extensibility from the rest produces a similar effect to a hole.

(2) The stress on cross sections may be rendered non-uniform by the local action of contiguous material. Thus, bars of the form D are known to break with a low apparent tenacity. The unstrained material *a* prevents the elongation of the adjoining material *b*, and virtually renders the material unhomogeneous. In the form E a similar action occurs; but here the less strained material on either side of the section of fracture hinders contraction so much as to raise the apparent tenacity (see § 33).

66. *Pin Grips.*—The oldest way of holding plate specimens is to drill a hole at each end and narrow the bar in the middle by slotting or milling. The test bars are then of the form A (Fig. 64). A steel pin in the jaws of the testing machine shackles passes through each pinhole in the specimen. This method of holding

plate specimens is convenient and satisfactory, especially when the test bar is of large size.

The pinholes must be accurately on the axis of the narrowed part of the bar to ensure uniformity of stress. But, besides this, it is important that the pins should be so large as not only to be safe against shearing, but so that the crushing pressure on the surface of the pinholes is not great enough to largely deform them. If this is not attended to the bar will almost certainly break from the pinhole across the enlarged ends, even when these are considerably larger than the narrow part of the test bar.

Let a be the area of section of the bar at $a\,b$, and d the diameter of the pin. Then, the shearing section of the pin will be sufficient if

$$\frac{\pi}{2} d^2 f_s = k f_t a,$$

where f_t and f_s are the tearing and shearing resistances of the plate and pin, and k a factor of safety not less than 3. If $f_s = f_t$,

$$d = 1{\cdot}38\sqrt{a}.$$

Thus, for breaking specimens of 4 sq. ins. area, a pin is required of $2\frac{3}{4}$ inches diameter.

Now let t = *thickness of test bar, and* f_c *the pressure* at which it crushes. Then, in order that the pinhole may be safe against deformation,

$$f_t\, a \text{ must be less than } f_c\, d\, t.$$

FIG 65

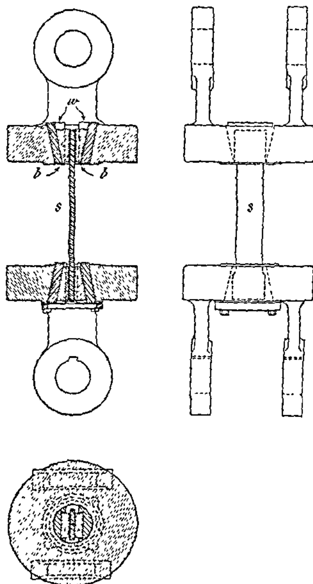
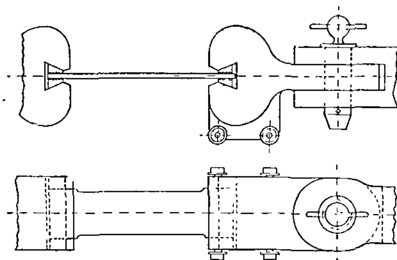


Fig. 66 shows the arrangement of the wedge-grip shackles in the Werder Machine. This shackle differs from those most used in this country—(1) in the short-

ness of the wedges; (2) in the slot in the shackle being open at the ends, so that any width of plate can be held. On the other hand, there is no provision for fairly

Fig 66



holding test pieces the faces of which are not parallel. Perhaps this is less important when the wedges are short. For with short wedges the serrations bite deeply into the bar, and so to a certain extent adjust themselves to a small defect of parallelism in the faces.

Riehle's Wedges.—In order to ensure the coincidence of the tension with the axis of the specimen, Messrs. Riehle Brothers, of Philadelphia, adopt a plan different from that used in this country. The shackle has a rectangular recess, so that the wedges which grip the specimen cannot swivel. There would, therefore, with ordinary flat-faced wedges be a likelihood that the wedges would grip the specimen more on one side than

Fig. 65.

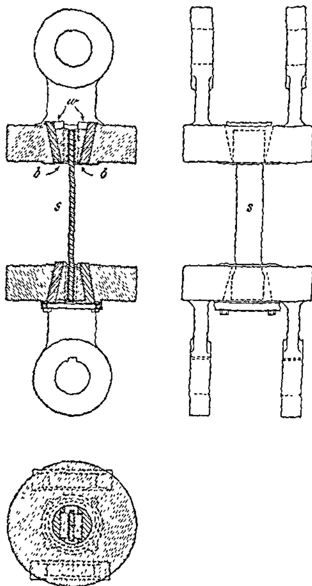
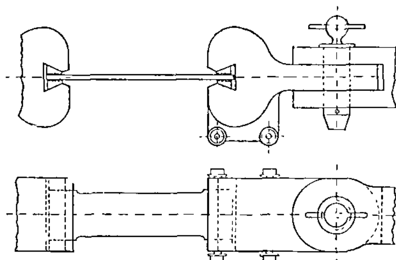


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FIG 66

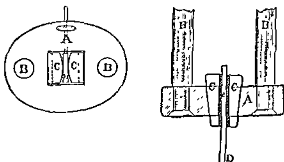


holding test pieces the faces of which are not parallel. Perhaps this is less important when the wedges are short. For with short wedges the serrations bite deeply into the bar, and so to a certain extent adjust themselves to a small defect of parallelism in the faces.

Riehle's Wedges.—In order to ensure the coincidence of the tension with the axis of the specimen, Messrs. Riehle Brothers, of Philadelphia, adopt a plan different from that used in this country. The shackle has a rectangular recess, so that the wedges which grip the specimen cannot swivel. There would, therefore, with ordinary flat-faced wedges be a likelihood that the wedges would grip the specimen more on one side than

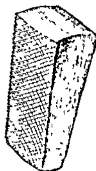
the other; in fact, if the specimen were thicker on one side they would inevitably do so. To avoid this the wedges are made with a round face.

FIG 67



The shackle is shown at A (Fig. 67), and the round-faced wedges at C, C, with the specimen between them: *e* is a pin used to adjust the specimen between the wedges. Fig. 68 shows on a larger scale the form of one of Riehle's wedges.

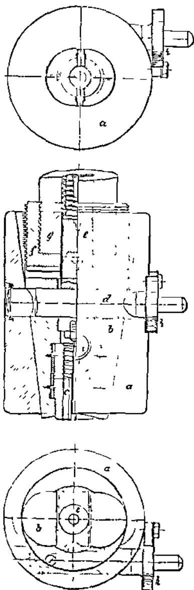
FIG 68



Shackles of the Emery Testing Machine. These are as original and ingenious as the other details of the machine, and more nearly comply with the conditions required for perfectly holding a test bar than any other shackle. Fig. 69 shows the shackle. *g* is the end of the press ram, or yoke, to which the shackle is to be attached. *f* is a nut forming part of the shackle. In the shackle two oblique cylindrical holes are bored, forming the seats for the sliding wedge pieces *b*. In these wedge pieces are fitted the various gripping

pieces *c*, to suit flat plates of different thicknesses or round or square bars. The wedges *b* slide so that their faces are perfectly parallel. The gripping pieces are cylindrical, so that they can adjust themselves to plates of unequal thickness. The wedges *b* are not, as in other machines, loose, but form a permanent part of the shackle; a toothed rack is formed on the side of them, engaging a pinion driven by the shaft *h*, so that they can be moved forward to grip the test piece. A ratchet and click prevents the slacking back. The wedges are traversed by a bar *d* carried by the rod *e*, which is pressed by a spring, against which the rotation of the shaft *h* moves them. Under *f* is an elastic packing to prevent injury by shock.

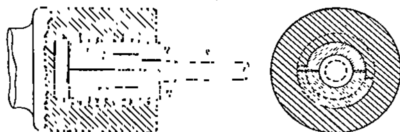
Fig 69



The gripping pieces *c* are each in two parts, the back part being roughened with teeth, the front part plain. This allows a certain stretch of the specimen in the length of the gripping pieces, and at the same time holds them by a double bite. This prevents fracture of the test piece inside the shackle.

68. *Colonel Maillard's Grips.*— In the Maillard machine very convenient grips are used in the form of

Fig 70

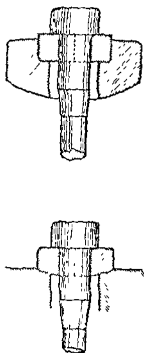


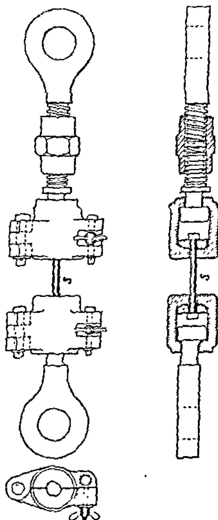
two half-rings *n*, *n*, screwed on the outside. The test bar is formed with shoulders at the ends. A pair of grips enclose the shoulder, and these are then screwed into the shackles of the machine. Fig. 70 shows these grips, which are extremely simple and convenient to use.

69. *Shackles with Spherical Bearing-surfaces.*—For very accurate experiments, especially for experiments on the modulus of elasticity, the coincidence of the tension with the axis of the bar is of great importance. It is best secured by carrying the bar on bearing-surfaces which are spherical. This has been done in several testing machines for round bars, but has not been accomplished for plates.

The easiest way of supporting round bars is to form

the Grafenstaden Engine Co., of Mulhouse. Two hinged boxes grasp the test bar, which is formed with shoulders.


Fig 72

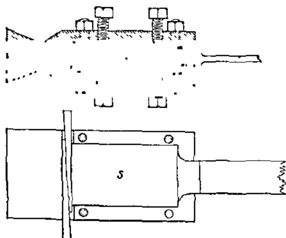

Fig. 73

Between the shoulders of the bar and the boxes half-rings with spherical seats are inserted, so that the bar may swivel into the line of pull.

70. *Bauschinger's Tension Shackle for Specimens of Wood.*—Fig. 74 shows a cast-iron shackle for specimens of timber used in Bauschinger's researches. The dovetailed end of the shackle fits into the ordinary tension shackle of the

testing machine. The shackle is in two halves, and the specimen is centred by the set screws. In order to get

FIG 74



a uniform distribution of stress in the neighbourhood of the shoulders, two thin wedges, or keys, are driven in at the back of the specimen.

71. *Kortum's Patent Rope Attachment.*—Ropes are amongst the most difficult of materials to hold satisfactorily in the testing machine. Fig. 75 shows a form of attachment which appears to have been used satisfactorily both for hemp and wire ropes. The figure shows an ordinary attachment, and not one made specially for testing. But shackles of precisely this kind, made somewhat more strongly, have been used in the testing laboratory at Berlin for testing ropes. By any process of splicing or knotting the rope is injured, or at least bending stresses are introduced which weaken the rope in the neighbourhood of the shackle.

Kortum's shackle consists of a conical shell or thimble, provided with a hook or loop, and having internal gripping wedges *k* which compress the rope between them. The wedges are so formed as to compress the rope concentrically, and, having a greater taper than the thimble, the pressure is greatest at the free end of the rope and least near the mouth of the thimble. Hence the bite on the rope increases regularly from the mouth backwards. The wedges have teeth on the inside, which indent the rope without sensibly injuring it near the mouth of the shackle. They are easily fixed, and adjust themselves automatically as the tension comes on the rope.

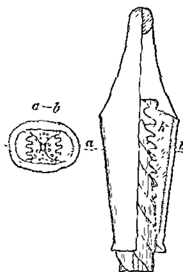


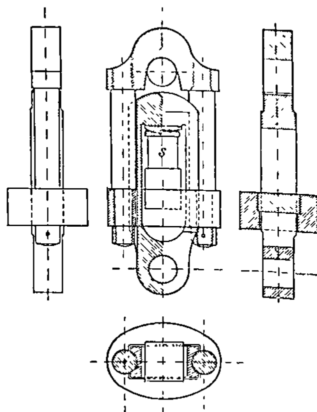
FIG 75

II. SHACKLES FOR OTHER TESTS.

72. Fig. 76 shows a crushing shackle, designed by the author for short specimens. There *s* is the specimen, a cube of stone, for instance, which rests between the two parts of the shackle. The pull on the shackles exerts a crushing force of equal amount on the stone. The shackles are guided by the side bolts, so that the opposite faces remain parallel. To distribute fairly the load on the stone block, which may be, to a small

extent, out of truth, a cup-and-ball distance piece, with well lubricated surfaces, is placed between the upper face of the stone and the shackle.

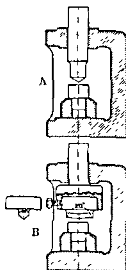
FIG 76.



73. *Kennedy's Torsion Shackle.* — Fig. 77 shows a form of friction grip used by Prof. Kennedy for holding specimens subjected to torsion; *s* is the specimen, held between two V-shaped fixed jaws and a third movable jaw. This last is centred eccentrically to the curvature of its surface, so that the slight rotation of the specimen,

purpose the plan generally used is to indent the specimen by a given load, and measure the depth of indentation. Major Wade used a hardened-steel pyramidal point, or knife-edge, as shown at A (Fig. 80), held in a guide-block which could be placed in the testing machine. A pressure of 5 tons was used to force the point or edge into the specimen, and the relative hardness was taken to be proportional to the volume of indentation. Colonel Rosset has improved this arrangement by adopting the form of point shown at B. The point consists of two knife-edges inclined at 163°, the angle of the knife-edges being 90°. Mr. Turner has used a quite different method. He fixes a diamond in a wooden lath, so that it rests normally on the specimen. The weight in grams which must be placed on the lath to cause the diamond to scratch the specimen is taken to be proportional to the hardness.

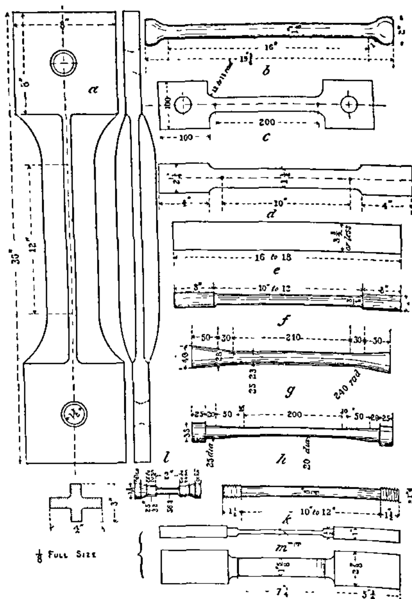
Fig. 80.



77. *Forms of Test Bars for Tension.*—In Fig. 81, *a* shows the old form, used by Hodgkinson for cast iron, with pin shackles; *b* shows a form suitable for cast iron, used by Professor Kennedy. For cast iron the author prefers the form *k*, with screwed ends and nuts with spherical seatings.

For ductile materials, such as wrought iron and soft

FIG. 81.



steel, the forms *c*, *d*, *e*, *f*, *g*, *h*, *k*, *l* are used, and the ordinary size of these is marked in metric or English

CHAPTER VI.

MEASURING INSTRUMENTS.

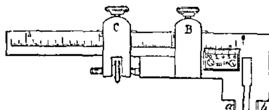
ORDINARY graduated measuring instruments are required in the engineering laboratory to determine the dimensions of test bars. In some cases the deformations (elongations, deflections, &c.) can be measured accurately enough by the same instruments. For the more accurate measurement of strains, however, special measuring instruments are required.

79. *The Graduated Straight-edge.*—Steel straight-edges of different lengths, graduated on the edge, are used for several purposes. For the rougher tests dimensions may be callipered, and the callipers placed on the graduated straight-edge. Extensions of ductile materials can be measured in a similar way. Two slight centre punch-marks are made on the bar, and the distance between these is taken by a beam compass, which is then placed on the graduated straight-edge. The differences of successive measurements are the elongations. The most convenient graduated straight-edges are made by the Brown & Sharpe Manufacturing Company, of Providence, U.S.A. These have gradua-

tions into $\frac{1}{10}$ inch and $\frac{1}{100}$ inch, and into millimeters and fifths of millimeters.

80. *The Straight Vernier Calliper.*—The beam compass of the draughtsman is very commonly graduated along the beam, and a vernier is fixed on the sliding head. The fault of the beam compass, however, is the springiness of the points, and want of perfect truth of the sliding surfaces of the beam. A straight vernier calliper is, in fact, a beam compass with very rigid points and a metal beam. Fig 86 shows the construction of

FIG 86



a vernier calliper as made by Messrs. Brown & Sharpe. A steel straight-edge of very accurate form is bent down at *b* to form one leg. On this slides very accurately the sliding head B, carrying the second leg *a*. For more accurately adjusting the position of the sliding head B there is a third slide C, which can be clamped to the bar, and from which the position of B can be adjusted by a fine-pitched screw. The face of B is cut away to show the scale, and the bevelled face of the slot is graduated as a vernier.

The most convenient graduation for English measures is for the scale to be divided into tenths, and each

tenth into quarters. A quarter-tenth reads twenty-five thousandths. If now on the vernier a length of twenty-five quarter-tenths is divided into twenty-five, the vernier *will read off thousandths of an inch.*

The outside diameter, or width, of bars is obtained by placing them between the jaws *a b*, and sliding the moving head till contact with gentle pressure is obtained. The calliper should be held lightly in both hands, and by slight movements it is easy to determine if the jaws are square with the bar to be measured. No excessive pressure must be used or the instrument will be injured. Inside diameters of rivet-holes and similar measurements may be obtained by using the rounded outsides of the jaws *a b*. There is *then a fixed quantity to be* added to the reading on the scale. Some callipers, however, have two verniers, so placed that one reads outsides and the other insides.

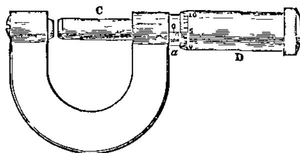
The steel vernier callipers of Messrs. Brown & Sharpe *are extremely useful and trustworthy, and will* even bear moderate rough usage without much injury. The shortness of the jaws is, however, sometimes inconvenient.

Instruments of the same kind, somewhat more finely graduated, *and with longer jaws and heavier slides*, are made by Messrs. Holtzapfel and Messrs. Elliott Brothers.

81. *The Screw Micrometer.*—This instrument (Fig. 87) is a kind of calliper, and is useful for determining the dimensions of the smaller test bars. *At one end of*

a bent frame is a fixed abutment, at the other a cylindrical bar C, moved by a fine-pitched screw. By turning the sleeve D, the bar C advances to or retires from the abutment An object to be measured is placed

FIG 87

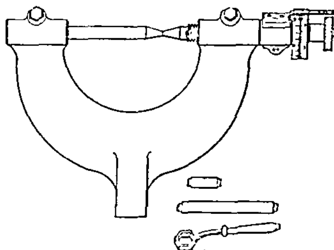


in the jaws, and C is advanced till there is contact with gentle pressure. Some tact is required, and it should be remembered that a force applied to the sleeve produces a much greater pressure between the jaws. There is a graduation along the straight cylinder at *a* into tenths of an inch and quarter-tenths, and the edge of the sleeve D is itself graduated into twenty-five divisions, each of which corresponds to a movement of the jaw of $\frac{1}{1000}$ inch. As the divisions are open, it is quite possible to read the scale by estimation to one-fifth of $\frac{1}{1000}$ inch. But although this reading is easy, it is not equally easy to ensure the delicacy of touch required for so great accuracy. In the Brown & Sharpe micrometer calliper the adjustment to zero, if the instrument wears, is effected by withdrawing the sleeve D, and applying a small wrench to a nut inside.

The instrument should be tried occasionally to see whether, when screwed home till the faces of the jaws touch, the scale really reads zero. If not, adjustment is required. The accuracy of this instrument depends entirely on the accuracy with which the fine-pitched screw is cut. When obtained from a really trustworthy maker the screw can generally be relied on to read accurately to the nearest $\frac{1}{1000}$ inch. Beyond this degree of accuracy, however, no screw can be trusted which has not been independently tested. Usually these instruments take between the jaws either 1 inch or 2 inches at most.

82. *Professor J. E. Sweet's Screw Micrometer.*—This instrument (Fig. 88) is made by the Syracuse Twist

FIG 88



Drill Company. It has a ratchet-threaded measuring screw, the working face of the screw-thread being

normal to the axis of the screw, and the back face inclined. The tops of the thread, both in screw and nut, are removed, so that after wear a perfect bearing is still obtained by closing the split-nut. A slight looseness of the nut will not affect the measurement, on account of the square bearing of the thread. The screw and nut are of equal length (3 inches), to ensure equality of wear. The screw is moved by a sleeve provided with a milled head and held between washers, one of steel and the other of felt, to produce an adjustable friction, so that equal pressure may always be obtained between the measuring points. The index-bar projecting over the divided circle is adjustable. The pitch of the most carefully made screw is more or less variable, and no two screws are absolutely of the same pitch. This error is corrected by inclining the index-bar forward for a screw of too fine pitch, backward for one too coarse. Each instrument is adjusted by the makers to a standard 1-inch distance-piece. The index-bar is mounted on a split-sleeve, threaded upon the extended end of the measuring nut with a thread of corresponding pitch. This allows the index-bar to be thrown backward or forward to a convenient position for reading, or even turned a half-revolution, if desired, to measure work on the lathe, and read the dimension in that position. The above, which may be termed the head-gearing, is used only for determining the fractional parts of an inch. Whole inches are measured by the aid of standard distance-pieces, furnished with the

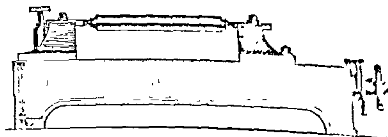
instrument. The tail-spindle is unclamped, drawn back, and a distance-piece inserted, and the spindle again clamped. No special pains need be taken to do this accurately, as the final adjustment is effected by setting the index-bar and its sleeve. The milled head is double, being graduated for $\frac{1}{1000}$ inch, and for binary fractions as small as $\frac{1}{64}$ of $\frac{1}{32}$, or $\frac{1}{2048}$ inch. The milled head by which the screw is turned is mounted freely on the spindle, and held between a washer of felt and one of steel dowelled upon the end of the spindle, and tightened by an adjusting screw. The friction thus produced secures uniform pressure between the measuring points, and eliminates the 'personal equation.' A variation of $\frac{1}{10000}$ inch can be recognised. The capacity of the instrument is 0 to 4 inches.

83. *Whitworth's Millionth Measuring Machine and Workshop Measuring Machine.*—These are fixed instruments, of heavier and much more accurate make than the ordinary screw micrometer. The screw has 20 threads to the inch, the screw wheel 200 teeth, and the micrometer wheel is divided into 250, so that each division represents $\frac{1}{1000000}$ inch. The end of the fast headstock and the end of the movable headstock are true parallel planes. The ends of the piece to be measured must also be true parallel planes. In measuring to an accuracy beyond $\frac{1}{10000}$ a feeling-piece is used. This is a piece of steel about $\frac{2}{16}$ inch thick, with parallel faces. It is introduced between the bar to be measured and the fast headstock. When proper adjustment has

been reached, the movement of one division of the micrometer wheel will set fast the feeling-piece. With [illegible] the feeling-piece it is said that a movement of [illegible] inch can be distinctly felt and gauged.

Fig. 89 shows a machine of this type of American construction (Richard's machine), with a [illegible] test piece in the jaws. The machine consists of a [illegible]

FIG 89



bed, something like a lathe-bed, with two headstocks, one fixed, the other moved by the accurate fine-pitched screw. The screw has a graduated head, and sometimes with a vernier also. The machines are guaranteed to be correct to $\frac{1}{10000}$ inch. They will read to $\frac{1}{25000}$ inch, but, without special means of ascertaining the pressure at the point of contact, such accuracy of reading is stated to be fallacious.

INSTRUMENTS FOR MEASURING STRAINS

84. In almost all experiments on the elastic properties of materials it is necessary to measure the strains or deformations which correspond to different stresses. Thus, in tensile tests the elongations are measured, in torsional tests the twist, in bending tests the deflection.

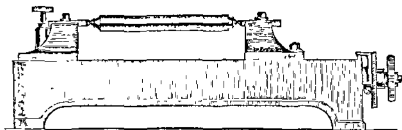
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been reached, the movement of one division of the micrometer wheel will set fast the feeling-piece. Without the feeling-piece it is said that a movement of $\frac{1}{40000}$ inch can be distinctly felt and gauged.

Fig. 89 shows a machine of this type of American construction (Richard's machine), with a standard test piece in the jaws. The machine consists of a solid

FIG 89



bed, something like a lathe-bed, with two headstocks, one fixed, the other moved by the accurate fine-pitched screw. The screw has a graduated head, and sometimes with a vernier also. The machines are guaranteed to be correct to $\frac{1}{10000}$ inch. They will read to $\frac{1}{25000}$ inch, but, without special means of ascertaining the pressure at the point of contact, such accuracy of reading is stated to be fallacious.

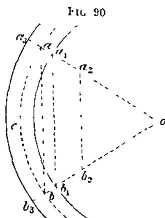
INSTRUMENTS FOR MEASURING STRAINS.

84. In almost all experiments on the elastic properties of materials it is necessary to measure the strains or deformations which correspond to different stresses. Thus, in tensile tests the elongations are measured, in torsional tests the twist, in bending tests the deflection.

In ordinary commercial tests of the quality of ductile materials, such as wrought iron and steel, only the ultimate permanent deformation is measured, and since, in such cases, this deformation is considerable, comparatively rough measurements are sufficient. Thus, if a soft-steel bar is broken by tension, the permanent stretching of an 8-inch length may amount to 2 inches. An error of even $\frac{1}{50}$ inch in measuring this would be only 1 per cent. of the elongation, and that is accuracy enough for practical purposes. Of course, for somewhat more rigid material, such as wrought-iron plates, the extension is less, and it is desirable to make the measurement more closely. But even in that case no very refined measurement is practicable, because of the difficulty of fitting together the broken pieces. To ascertain the strains in ductile materials during the progress of a test, after the elastic limit is passed, somewhat rough measurements are also sufficient. But it is altogether different in observing the strains within the elastic limit. A mild-steel bar, 10 inches long, is stretched less than $\frac{1}{100}$ inch when the elastic limit is reached For an accuracy of 1 per cent. the error of measurement must, therefore, not exceed $\frac{1}{10000}$ inch; and measurement to this degree of accuracy is more difficult than is commonly supposed. If the true elastic limit is to be determined, measurements to at least $\frac{1}{100000}$ inch are necessary. The smallness of this quantity may be realised by the aid of an illustration due to Sir J Whitworth: $\frac{1}{1000000}$ inch is only $\frac{1}{400}$ of the

thickness of a sheet of thin foreign letter-paper. In the case of standard measures of length, with bars of the most suitable form, the measurement, even to this degree of accuracy, is comparatively easy. But measurements of deformation have to be made on test bars of a form less suited for measurement and under conditions of some difficulty. Hence special methods are necessary, and instruments specially arranged for the purpose.

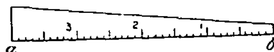
In the case of test bars, a difficulty of measurement arises out of the occurrence of a change of curvature of the bar during the test. The bar may initially have a small curvature, and be straightened by the load; or, if the load does not act accurately along the axis of the bar, it may become curved during the test. Suppose a bar curved like the bar in Fig. 90 in the plane of the paper. If the bar straightens by loading, the distance between a and b will increase, not only by the amount of the elongation, but by the difference of the chord and arc length $a\ b$. Suppose two clips fixed on the bar normal to its axis, and measurements taken between two points a_2, b_2. By straightening of the bar the clips will become parallel, and the distance $a_2\ b_2$ will be lengthened by the alteration of inclination of the clips still more seriously. It is important to



= 0·375 inch, we get $a_1 b_1$ = 9·991 inches, and the error due to straightening would not exceed 0·006 inch; a quantity much less, but still large enough to be of consequence in elastic measurements. If measurements are taken at points symmetrically placed on either side of the bar, the error due to curvature is nearly eliminated, the lengthening of the distance on one side being compensated by shortening on the other.

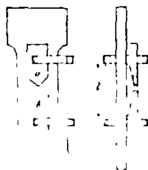
85. *The Wedge Gauge.*—The wedge gauge is a triangular plate, with sides sloping at 1 in 10, graduated

Fig. 91



along the longer side. If this is pushed between two pins, or shoulders, the distance between them can be read off on the scale, magnified by the ratio of the sloping sides ten times. Professor Eaton Hodgkinson used wedge gauges, and the author also used wedge gauges, for measuring extensions, about 1856. Two loose pieces, *a*, *b* (Fig. 92), were clamped on the test bar, and the wedge gauge pushed between them. They were made to bite into the test bar slightly at two points on the test bar, at a distance *l*. As the test bar extended, the wedge gauge slipped

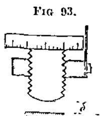
Fig. 92



further in, and the differences of readings gave the elongations to $\frac{1}{500}$ inch.

86. *Micrometer Screw Extensometer.*—A screw is equivalent to a wedge gauge in a more convenient form. It is virtually a wedge gauge wrapped round a cylinder. If p = pitch of screw, d = diameter of graduated head of the screw on which readings are taken, δ = the distance to be measured parallel to the axis of the screw, Δ the distance on the circumference of the head which corresponds to an axial movement δ, then—

FIG 93.



$$\frac{\Delta}{\delta} = \frac{\pi d}{p},$$
$$\Delta = \pi d \delta / p.$$

Let the screw have 25 threads to the inch (p = 0·04), and the head be about $2\frac{1}{2}$ inches in diameter, and divided into 100 parts of about $\frac{1}{10}$ inch each. Then each division corresponds to $\frac{1}{2500}$ inch, and can be read by estimation to quarter-divisions, or $\frac{1}{10000}$ inch. The accuracy of the instrument depends on the uniformity of pitch of the screw, which is often less accurate than it is intended to be. A difficulty also arises in consequence of the elasticity of the instrument. Differences of pressure at the point of contact cause differences of reading.

Professor Thurston[1] appears to have first used an

[1] *Materials of Engineering* Thurston Vol ii p 369

ensure proper adjustment in a plane normal to that of the micrometer screws, the centring screws *h h* are brought to bear on the surface of the test bar, after the rods *d d* have been thrown into gear, and the points of the micrometer screws placed over the centre of the contact-plugs. Then the centring screws are forced slightly into the test piece, so as to hold securely. After this, the side bars *d d* are gently removed, and the electric wires attached. The plane of contact of the micrometer screws and contact-plugs is in the middle of the measured length.

It is claimed for this apparatus that :—

(1) Its construction is symmetrical.

(2) It is applicable to various shapes of test bar.

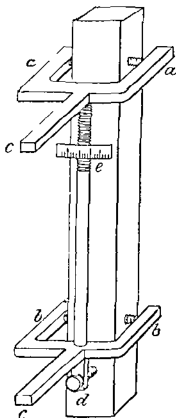
(3) It can be adjusted with certainty, so that the screws are symmetrical with the test bar.

(4) The micrometer screw-heads are of large size, giving readings of small extensions.

88. *Screw Extensometer with Levels.*[1]—Fig. 95 shows diagrammatically an arrangement the author has adopted, and which obviates most of the difficulty of employing a micrometer screw. Two clamps grip the specimen between pointed set screws, *a a* and *b b*, at points on a plane passing through the axis of the bar. The lower clip carries the micrometer screw *c*, on the hardened point of which the upper clip rests. If, then, the clips can be kept exactly normal to the axis of the test bar, the micrometer screw measures the distance between

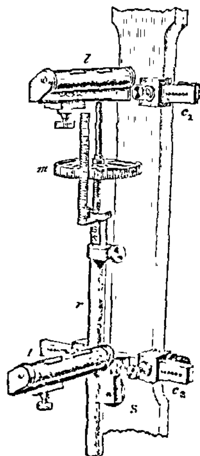
[1] *Proc. Physical Society*, vol. viii. p. 178

two points on the axis of the test bar—namely, the points on the intersection of *a a* and *b b* with the axis. Or, to put it another way, the micrometer screw being at the middle of the width of the clips, it measures the mean extension of the two sides of the bar. Now to set the clips accurately normal to the axis of the bar they are provided with delicate levels. Before taking a reading these are adjusted. The lower clip is first set level by the adjusting screw *d*. Next, the upper clip is set level by the micrometer screw *e*; lastly, the reading is taken on the graduated head of the micrometer screw. Fig. 96 is a general view of the instrument applied to a flat test bar. c_1 c_2 are clips; *l l* levels; *m* the micrometer screw; *r* a bar of adjustable length to suit different test bars. The instrument is very easy to use, the pressure on the micrometer screw is constant, being the weight of the upper clip; and lastly, the measurements are virtually measurements made on the axis of the bar, so that errors due to curvature are nearly eliminated. The instrument constructed reads to $\frac{1}{10000}$ inch.



89. *The Cathetometer.*—The cathetometer is an instrument for determining the difference of level of two points by a telescope sight. It may therefore be applied to determining the elongation of a bar under stress by reading the length between two fine diamond scratches before and after the stress is applied.

FIG. 96.



It consists of a telescope with cross wires, carrying a sensitive level, and sliding on a very accurately formed vertical slide. The slide is carried on a support, round which it can rotate. Suppose the axis of rotation adjusted accurately vertical, and the slide adjusted accurately parallel to the axis of rotation. Lastly, let the axis of the telescope be adjusted to the horizontal by the aid of its level-tube. Then if the telescope be set in succession on two points, and readings taken on a scale attached to the telescope-slide by a vernier attached to the telescope, the difference of the readings will be the difference of level of the points.

The cathetometer is for certain purposes extremely

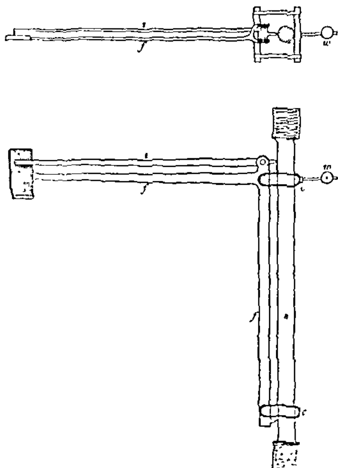
valuable. The readings are taken from any convenient distance, without its being necessary to touch or even approach the bar to be measured. The measurements are taken directly on an accurate scale, and are absolute measures, not needing any reduction, and not depending on any other measurements. On the other hand, in determining elongations or deflections the cathetometer is laborious in use. The need of taking two vernier readings for each measurement of the bar wastes a good deal of time.

The author has used a cathetometer by Breithaupt, of Cassel. This has a cylindrical central support, which can be set by a circular level indicating to 10 seconds. The prism on which the telescope slides is of cast iron, with an inlaid silver scale 1 metre in length, divided into millimeters. This prism is balanced by a weight on the other side of the axis of rotation. To adjust this prism accurately vertical a special separate adjusting-level of great sensitiveness is provided The telescope, fixed in Y's on a brass slide-block, is reversible, and carries a striding-level, also reversible. By a clamp and tangent screw the telescope cross wire can be brought into accurate coincidence with the object The block carrying the telescope has a vernier reading on the silver scale on the prism to $\frac{1}{20}$ mm. (or $\frac{1}{500}$ inch).

By means of a micrometer eyepiece a cathetometer may be used to read to $\frac{1}{10000}$ inch In connection with one of the testing machines at Berlin there is a

Kennedy's Lever Extensometer.[1]—Prof. Kennedy has designed and very largely used the simple lever extensometer shown in Fig. 100. This consists of a light frame

FIG. 100.



f carrying a simple lever *i*. The two steel points, one on the frame *f*, the other on the lever *i*, are 10 inches apart. These are placed in centre punch marks on the

[1] *Proc. Inst. of Civil Engineers*, vol. lxxiv; also lxxxviii. p. 21.

specimen *s*, the apparatus being held in position by elastic bands *c c*, a weight *w* helping to preserve the balance. The lever *i* turns on two set screw points, and the other end moves over a plane covered with section paper, attached rigidly by an arm to the frame on the test bar. As the piece extends the steel points move apart, turning the lever round its axis. The leverage is 100 to 1, and readings can be taken to $\frac{1}{1000}$ inch. The *ratio* of magnification was determined by measurement with vernier callipers.

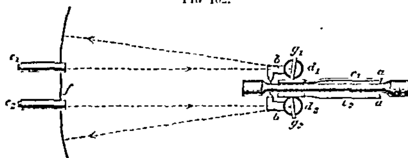
Dupuy's Extensometer for Actual Structures.[1]—The object of this apparatus is to ascertain by direct measurement the alterations of length of different members of iron structures by loads. Assuming that a bar of iron is elongated or shortened $\frac{1}{10000}$th part of its length by stress in tension or compression of 1·27 ton per sq. in., it is possible to calculate from the observed alterations of length the stresses in the bars produced by the loads. To the bar to be tested a fulcrum pin is attached, on which works a lever arm, with a leverage of 20 to 1, terminating in a pointer moving over a graduated arc carried by the fulcrum piece. To the short end of the lever is jointed a bar 1 metre (3·28 feet) in length, a pin at the other end of this bar being also attached to the bar to be tested. With the proportions adopted, each millimeter of movement of the pointer on the scale corresponds to a stress of a kilogram

[1] *Ann. des Ponts et Chaussées*, 5th series, vol. xiv p 331

In 1879 Prof. Kennedy exhibited at the Institution of Civil Engineers a two-mirror arrangement similar in principle to that of Dr. Streinitz.[1] But he has given up its use in favour of the lever extensometer already described.

93. *Bauschinger's Roller and Mirror Extensometer.*[2] To Prof. Bauschinger belongs the credit of first systematically taking double measurements on opposite sides of a test bar. A pair of clips, formed like parallel vices, are clamped on the bar at a and b (Fig. 102).

Fig 102.



These grip the bar between knife-edges. The clip b carries a pair of hard ebonite rollers d_1, d_2, on accurately centred spindles. The spindles are prolonged upwards and carry the mirrors g_1 g_2, which rotate in the plane of the figure as the spindles rotate. The rotation of the mirrors is measured by reading-telescopes e_1, e_2,

[1] 'Engineering Laboratories,' Kennedy. *Proc. Inst. of Civil Engineers*, vol lxxxviii p 22.

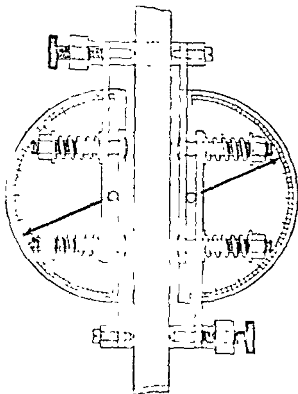
[2] *Maschine zum Prüfen der Festigkeit der Materialien, construirt von Ludwig Werder, und Instrumente zum Messen der Gestaltsveränderung der Probekörper, construirt von Joh. Bauschinger.* München, 1882. Also *Mittheilungen a. d. Mech. Techn. Laboratorium in München*, Hefte 1 und 3

and scales f at a distance of 10 or 15 feet. The scale-divisions, seen by reflection in the mirrors, cross the wire in the field of view of the telescope. The mirrors have vertical and horizontal adjustments for bringing initially the scale into the field of view of the telescope. To turn the rollers d_1, d_2 proportionally to the extension of the test bar, the clip a carries a pair of spring pieces c_1, c_2, which touch the rollers d_1, d_2. The face of these spring pieces is slightly roughened by a file or by attaching a strip of the finest emery-paper, and they turn the rollers by frictional contact. It will now be obvious that any extension δ of the distance between the vices a and b will cause a rotation of the mirror g through an angle δ/r, where r is the radius of the roller. The apparatus is equivalent to a lever apparatus having for small arm the radius of the roller g, and for long arm the double distance of the scale from the mirror. Suppose, for instance, as in one of Bauschinger's instruments, the radius of the roller is 0·3214 cm., and the scale distance 160·7 cm. Then the magnification of the extension is $(160{\cdot}7 \times 2) \div 0{\cdot}3214 = 1{,}000$. The scale is divided into fifths of centimetres. Each division has, therefore, in measuring extensions the value of $\frac{1}{500}$ millimeter, or about $\frac{1}{10000}$ inch. As it is possible to estimate tenths of divisions, the readings can be taken to $\frac{1}{5000}$ millimeter.

Since in Bauschinger's apparatus there are two mirrors, two readings are taken, giving the extensions on the two sides of the bar. The mean of these is

by springs, and between them is placed the wire roller, carrying a light index-finger. As the bar extends, the plates slide relatively and rotate the rollers. Mr.

FIG. 104.



Strohmeyer states that he has obtained good results with a wire of 0·015 inch circumference. Then, the graduated arc having divisions equal to $\frac{1}{150}$ of the circumference, each division corresponds to $\frac{1}{10000}$ inch extension.

Comparing Strohmeyer's apparatus with Bauschinger's, it is obvious that the most essential difference is

the extreme smallness of the rolling pin which Mr. Strohmeyer uses. That this is convenient may be easily granted. It is more difficult to believe that such very small wires can be trusted to be circular in section. Further, the absolute measurement of the elongations depends on the exact measurement of the diameter of this very small wire ; and this must in fact be impossible to anything like the same proportionate degree of accuracy as in the case of the larger rollers of Bauschinger.

It would seem, therefore, that Mr. Strohmeyer's apparatus is rather better adapted to cases where relative extensions only are required. To such cases Mr. Strohmeyer has applied it with remarkable skill. By its means he has determined the relative extensions of members of bridges, and of different parts of the skin of a ship and the shell of a boiler, under their ordinary loads.

96. *Instrument for Measuring the Compression of Short Blocks.*—For measuring the compression of short blocks, such as cubes of stone, extremely minute measurement is necessary. The author has employed the arrangement shown in Fig. 105, which combines lever and optical magnification, and at the same time gives by a single reading the mean compression of the two sides of the block.

A rectangular frame c_2 c_2, with adjustments for blocks of varying size, is clamped on the base of the stone cube by four pointed set screws. It carries an

used to resist twisting. Hence it is with some reservation that assent can be given to Professor Thurston's claim, that 'the machine is capable of revealing characteristic properties upon which to base sound practical judgment as to the relative usefulness of materials for the various purposes for which they may be required, and under the different conditions of their production or manufacture.' The test bar for this machine is a small cylindrical bar $\frac{1}{2}$ inch to $\frac{5}{8}$ inch in diameter, with square ends. It is placed in a pair of jaws, one connected with a heavily weighted pendulum, the other with a worm and wheel. By driving the screw-gearing one end of the specimen is rotated, and the twisting moment is balanced by the weighted pendulum, acting at the other end and is measured by the sine of the angle through which the pendulum is moved.

A drum covered with a sheet of specially ruled section paper is fixed to the worm-wheel shackle, and a pencil attached to the pendulum turns with it. Hence, the pencil traces on the drum a circumferential line proportional to the difference of motion at the two ends, or to the twist of the specimen. The pencil has another movement parallel to the axis of the test bar; as it rotates with the pendulum, it is forced by a guide curve to move a distance axially proportional to the twisting moment (sine of angle of inclination of pendulum). Hence, the pencil draws a stress-strain curve, the abscissae of which are the strains or angles of twist, and the ordinates the twisting moments. Professor

Thurston's machine is simple and ingenious, and its use enabled him to detect directly that when a load is applied, removed, and reapplied, the yield point is found to be raised. But the machine has defects. It is wrong in principle to take the register of the strain from the clips which hold the specimen. The crushing of the ends gets registered as part of the deformation. The arrangements do not secure perfectly that there is no longitudinal or bending stress. The friction of the pendulum journal and the momentum of the pendulum may both influence the results.

Professor Ewing's Experiments.—In 1880 Professor Ewing made some experiments in Japan on the stress-strain curve for small wires.[1] The wire was loaded by filling a bucket with water. A pencil attached to the wire marked a line on a sheet of paper, which at the same time moved transversely a distance proportional to the load. The paper was moved by a string attached to a float. The diagrams are very similar to the earlier diagrams of Thurston.

99. *The Polmeyer Autographic Apparatus.*—In 1882 the author saw at Dortmund a 50-ton tension testing machine, designed by Professor Polmeyer expressly for autographic testing. It is a pendulum machine, with a very long pendulum, having a ton weight at the end. As one end of the specimen is pulled by a hydraulic press, the other pulls on the pendulum, and the stress is related to the angular rise of the pendulum. It is easy

[1] *Proc Royal Society* 1880

to see that a paper connected by one wire to the pendulum, and a pencil connected by another wire to the specimen, can be so arranged as to draw a true autographic diagram.

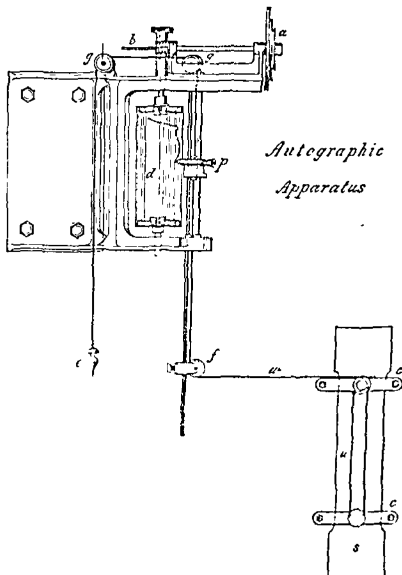
Fairbanks' Autographic Apparatus.—In Mr. Abbott's little treatise on Testing Machines there is described in considerable detail a large testing machine, constructed by Messrs. Fairbanks in America, with an autographic apparatus attached. The machine is a 100-ton machine, and adapted for tension, compression, bending, and other tests. It is a compound-lever machine, in which the final lever is a steelyard with travelling weight or counterpoise.

Now to effect the adjustment of the counterpoise on the steelyard to the stress on the specimen, a very ingenious electrical arrangement is used. As the steelyard rises or falls against its stops it completes an electric circuit, which starts an electro-magnetic engine, which moves the poise. Thus, if the lever rises, showing that the stress exceeds the load applied by the steelyard, the electro-magnetic engine moves outwards the counterpoise till, balance being restored, the circuit is broken. Geared to the arrangements for moving the counterpoise is a drum or cylinder on which the record is made, and the rotation of this drum is therefore exactly proportional to the movement of the counterpoise on the steelyard. Consequently, a pencil held fixed over the drum would trace a circumferential line the length of which is proportional to the load on the specimen.

The pencil, however, has a second motion parallel to the axis of the cylinder, derived from a thin flexible steel tape attached to two clips on the specimen. This is led off over pulleys, so as to move the pencil axially along the cylinder. The defect of the arrangement is that the elongation is not magnified, and the tape is so long that it is hardly possible it can give the pencil a quite true movement free from any error due to slack in the tape. It is stated, however, that the error does exceed $\frac{1}{100}$ inch.

100. *Mr. Wicksteed's Autographic Apparatus.*—This is an apparatus fitted to the Buckton testing machine, shown in Fig. 55, p. 131. The motion of the pencil which indicates the load is derived from the fluid pressure in the hydraulic press, and not from the weighing apparatus. A pipe from the hydraulic press F is led to a small cylinder like an indicator cylinder, with a piston of 1 sq. in. in area. This piston is controlled by a strong spring, 15 inches long when unloaded, 5 inches long when loaded with 22 cwt., the full pressure on the piston when the pull of the machine is 50 tons. During a test, as the pull and consequently the fluid pressure, increases, the spring is compressed, and the pencil P moves horizontally along the recording drum D. On the test bar *s* are two clips J J, and a wire attached to weights resting on the lower clip is carried over a pulley on the upper clip, and over the links G, finally serving to rotate the recording drum D by an amount proportional to the elongation. Hence,

Fig. 106.



the stress is weighed by a steelyard, on which there is a travelling jockey weight weighing one ton. This is driven by a large screw; consequently, the rotations of

the screw are exactly proportional to the movement of the weight, and to the stress on the specimen. It is from this screw that a vertical paper cylinder *d* is driven. A small catgut belt drives a worm, acting on a worm-wheel of 200 teeth on the paper cylinder. As the resistance of the paper cylinder is very small, the motion given by the belt is quite accurate, and it has this convenience, that by means of a stepped pulley *a* several scales are available for the diagram. Necessarily, the specimens vary in size and strength, and it is extremely convenient to enlarge the load scale of the diagram for small specimens, and diminish it for large ones. The pencil *p* slides on guides parallel to the axis of the paper, and it is connected to the specimen by a very fine wire *w*, kept strained by a counter-weight *e*. The wire is so fine that a counter-weight of 2 or 3 ounces is quite sufficient to keep the wire taut, and overcome the friction of the slides.

On the specimen *s* are two clips *c c*, the construction of which is so arranged that they are perfectly rigid in position on the bar, and which define exactly the length in which the elongation is taken, and do not become slack as the bar contracts It is extremely convenient to magnify, more or less, the elongation, so as to get a larger diagram. The author has tried several plans. That most generally convenient is very simple. The thin wire is attached to the top clip, taken over a pulley on the bottom clip, again over a pulley on the top clip, and then horizontally to the guide pulley *f* on

the corresponding load can easily be read off. And the record in this way is effected with great ease and rapidity.

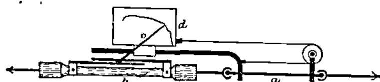
Fig. 107 shows one of the diagrams obtained, and contains a record of more than 150 extensions, taken in less than half an hour. Half the readings are taken with an increasing load, the other half while the load was being removed. The figure is about one-fourth the actual size of the diagram, and the steps correspond to $\frac{1}{3000}$ inch of extension. The diagram is one of the first taken in this way by students at the Central Institute. It is not a particularly perfect diagram, but it illustrates the kind of record obtained by this method.

103. *Professor Kennedy's Autographic Apparatus.*—An apparatus devised by Professor Kennedy and Mr. A. G. Ashcroft is of a different kind. The following description is taken from Professor Kennedy's paper:[1]—The apparatus cannot be said to be suitable for general use, but for a laboratory, where it is in skilled hands, and not subject to rough usage, Professor Kennedy believes it to give more trustworthy diagrams than any of the other forms yet devised. It has also the advantage that it is wholly independent of either the poise or the ram, or even any part of the framing of the testing machine, and that its own parts are so light that the diagram may be assumed to be free from any errors due to inertia. The test-piece *a* (Fig. 108) is placed in

[1] *Proc. Inst. of Civil Engineers*, vol. lxxxviii. p. 30. A detailed drawing of the apparatus is given

the machine *in series* with a stronger bar *b*, called a spring piece, and the two, which are connected directly by a simple coupling, are pulled simultaneously, the one through the other. The spring piece is of such a material that its limit of elasticity occurs only at a load greater than that which will break the test piece. It must also be of material ascertained by previous experiment to be perfectly elastic, so that its extension is strictly proportional to the pull on it, and therefore to the pull on the test bar. By a simple arrangement a very light pointer *c* is made to swing about an axis

FIG 108



through an angle proportional to the extension of the spring piece, and proportional, therefore, to the pull on the test bar. The end of this pointer touches a sheet of smoked glass *d*, to which is given a travel—in its own plane—proportional to the extension of the test piece, and in this way the diagram is drawn After the experiment the glass is varnished to fix the black, the necessary particulars are written on it with a scribing point, and the whole is used as a negative, and multiplied by photography.'

Some of the diagrams taken with this apparatus are shown in Fig. 28, p. 67. It is a small and not serious

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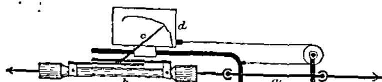
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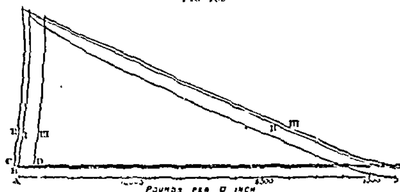
Some of the diagrams taken with this apparatus are shown in Fig. 28, p. 67. It is a small and not serious

objection that the load ordinates are curved. The great merit of the instrument is the very perfect registration of the stress, free from errors due to any accidental action of the machine.

Some particulars of a machine acting in a similar way, and taking a very small diagram, which could afterwards be magnified, were given by Herr Martens in the correspondence which is appended to Professor Kennedy's paper.

Elastic-strain Diagrams.—The only apparatus for drawing purely autographic diagrams of the strains within the elastic limit is also devised by Professor Kennedy. It acts on the same principle as the last

Fig 109



apparatus, but the swinging pointer is placed on the test piece and used to record its extensions. The frame is carried by the test piece, and is moved by the poise-weight of the testing machine.

Fig. 109 shows three elastic strain diagrams taken by this apparatus for a piece of cast iron 0·75 inch in

inches long. The distance A B is the
loading. There is a small further set,
loading. Exaggeration of extension,

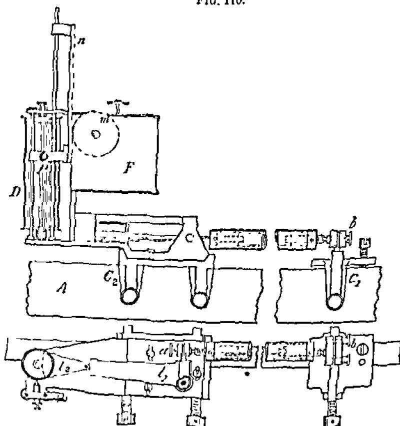
hic Extensometers, recording Time and
attempts have been made to study ex-
tion of a travelling load on a structure
In such cases the train which forms
moves with uniform speed across
member of which passes through a
stress related to the position of
f a diagram can be drawn with the
or compressions) as ordinates and
it is possible to infer the stresses
ch position of the moving load.
of this kind was designed by Dr.
nstructed by Oscar Leuner in

gram of the instrument. Two
ed to the member of the structure
to be recorded. Between these is
... link attached to the clip C_1 at b, and acting at the other end a on the unequal-armed lever l_1. The lever l_1 is toothed at the edge and drives the lever l_2, and this, in turn, gears with a small pinion on the spindle of the drum D. The levers form a spur-wheel train magnifying the extension 200 times, and the drum D moves under the pencil P a distance proportional to

[1] *Civilingenieur*, 1881, vol. xxvii § 250.

the strain. The clock F at the same time moves the pencil axially at a uniform speed, driving the pinion *m* and rack *n*. Consequently, a diagram is obtained with

Fig. 110.



abscissæ proportional to the time and ordinates proportional to the strain.

The most ingenious mechanical contrivance in Dr. Frankel's instrument is that by which loss of time, or backlash in the spur-wheel multiplying gear, is prevented. Each toothed driver consists of two parts, connected by a spring only, which presses one part

forwards and the other backwards against the two faces of contiguous teeth of the driven wheel. There is always contact, therefore, between driving and driven teeth for motion in both directions, and any motion in either direction is communicated instantly and without loss of time.

Autographic Deflectometer of Askenasy.—This is a small apparatus for drawing the deflection curve of a beam during the passage of a load over it. A paper recording-drum, moved by clockwork, is clamped on the beam or bridge. An independently supported style traces a curve on the drum. The style is on a vertical rod, at any point of which it can be fixed, and this can be clamped to a wooden beam supported independently of the deflecting beam. The curve has time abscissæ and deflection ordinates.

CHAPTER VIII.

ELASTIC CONSTANTS FOR METALS.

105. THE accurate determination of the coefficients of elasticity and limits of elasticity depends on the measurement of extremely small deformations. Some of the practical difficulties of measurement have been discussed in Chapter VI. These difficulties are not the only ones in the path of the experimenter. For many materials the elastic constants change with the amount of stress applied and with every repetition of stress, and, to add to the confusion, there is not complete agreement as to the definition of the constants or the methods of determining them.

The nature of the coefficients of elasticity has been explained in Chapter I. Let it be proposed from observations on a bar of cast iron to determine its coefficient of direct elasticity. When a bar is subjected to simple longitudinal stress, the coefficient of direct elasticity E is the ratio of the stress p per unit of section to the extension or compression l per unit of length. That is, $E = p/l$. But the total extension of an inch of bar l consists of two parts—an elastic extension e, and a plastic extension or set s. If the bar is again strained,

the set s will be smaller and the modulus of elasticity p/l will be different. What is, then, the real coefficient of elasticity?

If a coefficient of elasticity $E' = p/e$ is calculated, values will be obtained which vary less with repetition of loading than the values of E. In most cases, also, E′ will be more constant than E for different ranges of stress. Hence it is a temptation to an observer to get rid of the sets, and to give values of the coefficient of elasticity which are values of E′, not values of E. Virtually this is often done; and either the sets are determined and deducted from the extension used in calculating the coefficient of elasticity,[1] or, what amounts to the same thing, the bar is loaded once or twice nearly up to its elastic limit before proceeding to measure the extension used in calculating the coefficient of elasticity.

The following table contains Hodgkinson's results for the tension and compression of long bars of cast iron These results on long bars are chosen because, although the methods of measurement were somewhat crude and rough, they are free from any possible objection arising out of complexity in the measuring apparatus. It will be seen that both E and E′ diminish as the stress increases, but that E′ varies much less than E. The coefficients are in tons per sq. in. The next table contains some results on bars of gun-barrel steel,

[1] See Lanza's statement as to what is done at Watertown *Applied Mechanics*, p 410

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the set s will be smaller and the modulus of elasticity p/l will be different. What is, then, the real coefficient of elasticity?

If a coefficient of elasticity $E' = p/e$ is calculated, values will be obtained which vary less with repetition of loading than the values of E. In most cases, also, E′ will be more constant than E for different ranges of stress. Hence it is a temptation to an observer to get rid of the sets, and to give values of the coefficient of elasticity which are values of E′, not values of E. Virtually this is often done; and either the sets are determined and deducted from the extension used in calculating the coefficient of elasticity,[1] or, what amounts to the same thing, the bar is loaded once or twice nearly up to its elastic limit before proceeding to measure the extension used in calculating the coefficient of elasticity.

The following table contains Hodgkinson's results for the tension and compression of long bars of cast iron These results on long bars are chosen because, although the methods of measurement were somewhat crude and rough, they are free from any possible objection arising out of complexity in the measuring apparatus. It will be seen that both E and E′ diminish as the stress increases, but that E′ varies much less than E. The coefficients are in tons per sq. in. The next table contains some results on bars of gun-barrel steel,

[1] See Lanza's statement as to what is done at Watertown *Applied Mechanics*, p 419

CHAPTER VIII.

ELASTIC CONSTANTS FOR METALS.

105. The accurate determination of the coefficients of elasticity and limits of elasticity depends on the measurement of extremely small deformations. Some of the practical difficulties of measurement have been discussed in Chapter VI. These difficulties are not the only ones in the path of the experimenter. For many materials the elastic constants change with the amount of stress applied and with every repetition of stress, and, to add to the confusion, there is not complete agreement as to the definition of the constants or the methods of determining them.

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made by the Committee on Steel, and which are chosen for similar reasons. For wrought iron and steel the set in the earlier part of the test is comparatively insignificant. Yet E′ is more constant than E, even in the earlier part of the test, and is nearly constant even for stresses considerably beyond the elastic limit. For wrought iron and steel E diminishes almost to zero as the breaking weight is approached.

EXPERIMENTS OF STEEL COMMITTEE

(Bars, 1½ inch in diameter Extensions and compressions in 10 feet)

Stress, in tons per sq in. p	Total extension, in feet $120\,l$	Set, in feet $120\,s$	Elastic extension, in feet $120\,e$	Ordinary coefficient of direct elasticity E	Coefficient E′
			TENSION		
6 80	0053	—	—	12,830	12,830
7·94	0062	—	—	12,800	12,800
9 07	·0071	0001	0070	12,770	12,960
10 21	0079	0002	0077	12,920	13,260
11 34	·0089	0002	0087	12,750	13,030
12 48	·0098	0003	0095	12,740	13,140
13 61	·0108	0004	0104	12,600	13,090
17 01	0143	0016	0127	11,900	13,400
			PRESSURE		
6 92	0047	—	0047	—	—
10 38	0078	0001	0077	13,300	13,480
13 84	0105	0003	0102	13,180	13,670
15 28	·0117	0006	0111	13,060	13,770
16 15	0125	0007	0118	12,920	13,690
17 31	0138	0011	0127	12,540	13,620
18 46	0172	0035	0137	10,740	13,480

No doubt in most cases values of E are given as the coefficient of elasticity, and it will be understood that it is so in what follows. But then materials like cast iron and all the brasses and bronzes have no definite coefficient of elasticity.

made experiments on the change of the coefficient with change of temperature. He found that it decreased about 0·03 per cent. for each degree rise of temperature (Centigrade). After a permanent stretching of the bar it diminished by 4 to 9 per cent.

COEFFICIENT OF DIRECT ELASTICITY OF IRON AND STEEL FROM TENSION EXPERIMENTS

—	Probable percentage of carbon	Coefficient E, in tons per sq in Initially	After heating to slight redness
Hammered Bessemer steel	1 35	—	14,220
,, ,, ,,	1 26	13,450	13,640
,, ,, ,,	1·05	13,660	14,060
,, ,, iron	0·1	14,430	—
,, ,, ,,	0 15	15,290	15,440
Rolled cast steel	1·22	13,940	—
Krupp ,,	0 61	14,000	14,340
Rolled puddled steel	0 66	—	13,540
,, ,, ,,	0 56	13,360	—
Lowmoor iron	0 2	14,280	—
Dudley ,,	0 09	12,680	—
,, ,,	0 09	12,260	—
Motala ,,	0 05	13,510	13,740
,, ,,	0 2	13,200	—
Surahammar iron	0 14	13,880	—
,, ,,	0 2	13,610	13,720
Charcoal iron (Aryd)	0·1	11,960	—
,, ,, ,,	0 1	12,410	13,050
,, ,, (Hallstahammar)	0 07	12,940	—
,, ,, ,,	0 07	13,760	13,760

108. The following table[1] gives values for steel, obtained by Bauschinger, and the tables are interesting as giving the coefficient for bending, tension, and pressure. The coefficient of rigidity was also determined by experiments on torsion. From the values of

[1] Reduced from tables in *Civilingenieur*, 1870.

E and G we can deduce values of Poisson's ratio *m*. (See §§ 4 and 10.)

COEFFICIENT OF ELASTICITY. BESSEMER STEEL FROM TERNITZ.

Percentage of carbon	Coefficient of direct elasticity, E				Coefficient of rigidity, C	$m=\frac{E}{2C}-1$
	From tension tests	From pressure tests	From bending tests	Mean	From torsion tests	
0 19	13,780	16,540	13,020	14,730	5,575	32
0 46	14,300	14,640	13,090	14,220	5,420	·30
0 54	13,690	16,140	12,900	14,480	5,450	·33
0·57	13,720	14,290	13,080	13,840	5,320	·30
0 66	14,480	15,940	14,350	15,010	5,520	·36
0 78	14,980	14,480	13,460	14,480	5,405	34
0·80	13,660	14,440	14,730	14,160	5,670	·25
0 87	13,880	14,100	13,590	13,900	5,400	·29
0 96	13,820	14,640	13,080	13,970	5,560	·26
					Mean	0 305
(?)[1]	14,740	14,800	13,960	14,500	5,625	0 29

SIEMENS-MARTIN STEEL FROM NEUBERG-MARIAZELL.

Degree of hardness	Coefficient of direct elasticity, E			Coefficient of rigidity, C	$m=\frac{E}{2C}-1$
	From tension tests	From bending tests	Mean		
7	13,450	13,520	13,460	5,470	25
6	13,090	13,340	13,210	5,260	·25
5	13,370	13,480	13,400	5,295	·27
4	13,390	13,430	13,400	5,401	·24
3	13,620	13,390	13,340	5,150	·30
				Mean	0·262

The following values are from experiments at Watertown Arsenal, and are, it is believed, values obtained after deducting the permanent set. They are values of E′ therefore.

[1] Bessemer steel from Teschen.

In commercial testing of iron and steel some rough estimate of the elastic limit is usually made. Thus, it has been proposed to take the elastic limit at the stress at which peeling of the skin is first visible (Styffe, p. 36), or at the stress at which the testing machine lever drops (Kennedy), or at the stress at which a rough measurement of the elongation by compasses is first possible (Lanza). All these measures are extremely rough, and what they really determine is the yield point, not the elastic limit. In almost all tables *what is given as the elastic limit is the yield point*, and this may differ from the limit of proportionality to any extent. Moreover, for materials other than wrought iron and steel there is no definite yield point. Where there is a yield point it is best determined from an autographic diagram.

110. The only definition which agrees with the theoretical conception of an elastic limit, and which is practically available in testing, is that which makes the elastic limit to be the stress at which proportionality between the stresses and strains first visibly ceases when measurements of considerable delicacy are being made. Bauschinger has re-adopted this definition, and it is to his observations chiefly that we must look for any knowledge of the elastic limit thus defined.

The following measurements of the extension of a piece of iron from old Hammersmith Bridge will show how the limit of proportionality can be determined. In this case the limit in successive loadings, none of which reached much beyond the elastic limit, slowly rises.

Link from old Hammersmith Bridge, received from B. Baker, Esq.

This was planed all over to get surfaces for accurate measurement, and its section was about $1\frac{3}{4}$ sq. in. Extensions for each ton, taken with mirror apparatus :—

Load in tons per sq. in.	Distance of gauge points, 7·91 inches. Extensions per ton in $\frac{1}{100000}$ths of an inch			
	First loading	Second loading	Third loading	Fourth loading
1	—	—	—	—
2	55	58	54	58
3	57	56	56	56
4	58	58	58	58
5	58	57	58	58
6	58	58	58	58
7	58 E. L.	57	58	58
8	61	59 E. L.	58 E. L.	58
9	60	60	60	58 E. L.
10	62	60	59	60
11	—	—	—	63
12	—	—	—	75
Set, load removed	+13	−2	+2	+32

	Total extension	Mean extension per ton
1st loading, 1 to 7 tons .	0·003437	0·000573
2nd " 1 to 7 " . .	0·003449	0·000575
3rd " 1 to 8 " . .	0·003996	0·000571
4th " 1 to 9 " . .	0·004619	0·000577
Mean		0·000574

Coefficient of elasticity, $7{\cdot}91/{\cdot}000574 = 13{,}830$.

111. So long as the limit of proportionality is not exceeded, the value of the coefficient of elasticity in ordinary metals is tolerably constant in successive loadings. The following are extensions in successive loadings of two pieces of Hammersmith Bridge links :—

—	Extensions for six tons		
	First piece	Second piece	Second piece, after three days
1st loading	·00344	·00346	·00341
2nd ,,	00345	·00343	·00342
3rd ,,	·00342	00347	·00340
4th ,,	00338	·00339	·00343
5th ,,	—	—	00342
6th ,,	—	—	00344
7th ,,	—	—	·00343

If, however, the yield point is passed, the limit of elasticity very sensibly alters, as is shown in the following results deduced from Bauschinger's tables. A plotting of some of these is given in Fig. 40, p. 102.

ELASTIC LIMIT, IN TONS PER SQ. IN., IN BARS LOADED UP TO THE YIELD POINT.

Material	Original state First loading	Second loading	Third loading	Fourth loading
Bars loaded, unloaded, and reloaded immediately				
Weld iron .	8 98	6·41	6 66	6·90
Ingot iron .	15 78	—	4 01	4·12
,, .	16 91	2 58	6 57	6 77
Copper . .	2 45 [2]	3·59	3·92	5 11
Bronze . .	3 43	4·06	4·13	—
Bars loaded, unloaded, and reloaded after a pause of 2½ to 80 hours				
Weld iron .	8·98	12·94	15·84	17·45
,, .	10 34	12 29	17·45	20·35
,,	10 22	14 22	15·78	18 94
,, .	10 30	(6 57) [1]	18 80	(6 81) [1]
Ingot iron .	15 09	5·13	7·92	6 83
Bessemer steel	11 60	19·32	(3 91) [1]	6 69
Copper .	1·14 [2]	3 27	3·61	5·14
,, . .	2 61 [2]	3 59	4·62	6 87
Bronze .	2 50	4 07	3 82	—
Bars loaded, unloaded, subjected to vibration, and reloaded after a pause				
Weld iron .	12 38	11·93	14·89	11·14
,,	8·98	11·93	12 13	8·28
Ingot iron	15 15	5·18	5 26	5 39
,,	16 48	19 56	17·10	17·60

[1] No pause between loadings

[2] Yield point not reached.

CHAPTER IX.

CAST IRON

112. DOWN to a recent period the ferrous materials used in construction could be divided into three groups, marked equally by difference of manufacture, of chemical composition, and of mechanical properties. Cast iron, the product of the blast furnace; wrought iron, the product of the puddling forge, and steel, produced from wrought iron by cementation, had characteristics so marked that it mattered little which of their differences was taken as a basis of classification. As their content of carbon seemed essentially connected with their properties, that was generally selected as a means of discrimination.

As to cast iron no difficulty arises; both its method of production, its properties, and its engineering uses leave it in a class apart. It is otherwise with wrought iron and steel. Since the development of the Bessemer and Siemens-Martin processes an essentially new material has been introduced, which is commonly and commercially termed steel, but which differs from the

older material of that name. The plates and bars of so-called steel, which are superseding in construction the old wrought iron, contain carbon, but in a quantity varying without break, in different cases, from a percentage as small as that in wrought iron to a percentage as high as that in cementation steel. Such plates vary in tenacity from that of wrought iron to a tenacity at least double that of wrought iron. Lastly, by far the larger part of this new material has not the characteristic property of the older steels of hardening when suddenly cooled.

There is, however, a difference between wrought iron and the new material which is replacing it important enough to justify a difference of classification. Wrought iron, and cementation steel as made from wrought iron, have been in the condition in the puddler's forge of granular or spongy masses bathed with liquid slag. This slag is never entirely got rid of, and remains in the forged material, not in great quantity indeed, but so distributed as to give rise to a visible structure. Bessemer, Siemens-Martin, and crucible steel, on the other hand, have all been fused and more perfectly cleared of mechanically mixed impurity. They have, when rolled, a homogeneousness and absence of grain which is definite and important. If the difference between puddled and cast material is recognised it will be found that there are two parallel series of products, first clearly arranged by M. Greiner, of Seraing:—

Percentage of Carbon			
0·0 to 0·15	0·15 to 0·45	0·45 to [illegible]	[illegible]
Series of the Irons			
Ordinary iron	Granular iron	Puddled steel	[illegible]
Series of the Steels			
Extra soft steel	Soft steel	Half soft steel	Hard [illegible]

This classification ignores the property of tempering as a mark of distinction between iron and steel, which is in some respects inconvenient. Hence in Germany it is becoming common to class one series as weld metal, the other as ingot metal. Weld iron and ingot iron are those materials which will not temper; weld steel and ingot steel those which harden when suddenly cooled.

113. *Constituents of Cast Iron.*—Cast iron consists of iron mixed or combined with carbon, silicon, manganese, sulphur, and phosphorus. Popularly, and with partial truth, the carbon is regarded as chiefly determining its characteristics. The carbon exists in cast iron either combined with the iron or mixed with it in the form of graphite. The greyer irons contain most graphitic carbon, and are weaker, more fusible, and softer than whiter iron. The white iron contains most combined carbon; but the other constituents have an influence on the mechanical properties The composition of cast iron varies within the following limits, if extreme qualities, unsuited for foundry use, are excluded :—

The density varies with the composition in the following way :—

Material	Density	Weight of a cubic foot, in lbs
Dark grey foundry iron	6·80	425
Grey " "	7·20	450
Mottled " "	7·35	458
White iron	7·60	474

The specific heat is 0·140 for grey iron, and 0·127 for white iron. Cast iron melts at about 2,732° Fahr.

114. *Mechanical Properties of Cast Iron.*—The elastic properties of cast iron have already been discussed. In tension and compression tests there is strictly no range of stress for which the stresses and strains are proportional, and there is no fixed coefficient of elasticity or elastic limit. It has, however, already been shown that the extensions and compressions are nearly the same for equal stresses (§ 26).

Mr. Hodgkinson found that the relation of stress and strain in cast iron was given very nearly by the following equations. Let p be the stress in tons per sq. in., e the extension, and c the compression per unit of length. Then—

$$p = 6{,}220\, e - 1{,}298{,}000\, e^2$$
$$= 5{,}773\, c - 233{,}500\, c^2.$$

The author has found the following inverse relations still more exact :—

$$e = 1\cdot503\, p^3 \times 10^{-6} + 1\cdot685 p \times 10^{-4}$$
$$c = 9\cdot66\ \ p^3 \times 10^{-8} + 1\cdot782 p \times 10^{-4}.$$

These are from experiments on very long bars. For 8-inch bars—

$$e = 0{\cdot}39\,p^3 \times 10^{-6} + 1{\cdot}62\,p \times 10^{-4}.$$

The following table gives a few measurements of extension in short cast-iron bars. The cast iron was the ordinary mixture of a good foundry :—

EXTENSIONS OF CAST-IRON BARS

(Extensions in 8 inches, measured by touch micrometer Bars screwed at ends and fixed in nuts with spherical seatings.)

Load in tons	Diam 1 0005 Area ·7862	1 005 ·7862	·999 ·7832	1 000 7854	·999 ·7842	·993 ·7743
	Extensions in 8 inches, in inches					
2·5	0043	0036	0034	0037	·0039	·0034
4·5	0073	0069	0062	0069	0074	·0061
5 5	·0093	0087	0080	·0089	0096	·0083
6·5	·0114	0107	0105	0112	0116	0101
7·5	0139	0132	0134	·0142	0147	0131
8 5	0168	—	—	—	—	—
9 5	·0215	—	—	—	—	—
	Extensions per ton in 8 inches, in inches					
2 5	00172	00144	00136	00148	·00156	00136
4·5	·00162	00153	00138	00153	00165	00136
5 5	·00169	00158	·00145	00162	00175	00151
6 5	00175	00165	00162	00172	00178	00160
7·5	·00185	00176	00178	00189	00196	00175
8 5	00196	—	—	—	—	—
9 5	00226	—	—	—	—	—
Breaking weight, in tons per sq in	12 94	14 37	13 87	13 04	14 21	13 90

115. *Ultimate Tensile Strength of Cast Iron.*—Tensile tests give much the best indication of the quality of cast iron for structural purposes. The crushing strength is greatest in qualities of iron quite unsuitable for foundry use, and the transverse strength depends in part on the crushing strength.

minimum tenacity of 12 tons was stipulated for, and only Cleveland iron was used.

Some qualities of iron are greatly improved by remelting or by being kept long in fusion. The following results were obtained by Major Wade :—

Fusion	Pig 1st	2nd	3rd	4th	5th
Tenacity in tons per sq. in.	5 to 6½	9·32	11·06	11·96	12·45

116. *Crushing Strength of Cast Iron.*—Hodgkinson used for compressive tests small cylinders and square and triangular prisms, having heights equal to from one to three times the transverse dimensions. He placed a sheet of lead on the faces of the prisms. It is not clear that this may not have diminished the strength. The most common form of fracture is shearing at an oblique plane making an angle of about 56° with the axis.

The crushing resistance is much increased if the height is so decreased that the plane of least resistance to shear cuts the faces at which the pressure is applied. The following results were obtained by Hodgkinson on cylinders ½ inch in diameter :—

Height of cylinder, in ins	⅛	¼	⅜	½	¾	1½	2	3¾
Crushing strength, in tons per sq. in.	69·3	63·5	60·0	55·0	53·3	53·3	49·6	34·4

The strength is pretty uniform if the height is between one and three diameters.

117. *Transverse Strength of Cast Iron.*—Tests by cross-breaking are so easily made that this kind of test has been very generally adopted as the commercial test

CRUSHING RESISTANCE OF CAST IRON.

Authority	Form of test piece	Transverse dimensions, in inches	$\frac{\text{Height}}{\text{Width}}$	No. of tests	Crushing strength in tons per sq. in			—
					Highest	Lowest	Mean	
Hodgkinson	Cylinders and prisms	$\frac{1}{4}$ to $\frac{3}{4}$	1 to 3	—	64·9	36·5	48·0	'Brit. Assoc. Rep.' v. VI. 1837
"	Cylinders	$\frac{3}{4}$	1 to 2	81	53·8	24·7	38·5	'Com. on App. of Iron,' 1849
Woolwich .	Cylinders	0·6	2	273	62·5	19·8	40·6	Report, 1858
Wade .	—	—	—	—	74·5	44·6	—	Thurston, 'Materials of Construction'
Turner	Cylinders	0·75	3	11	92·5	34·1 [1]	—	'Journ. of Chem. Soc.' 1885
Fairbairn .	—	—	—	—	95·9 [2]	—	—	—

[1] Series of special test bars, with varying percentage of silicon.
[2] Highest result after repeated remeltings.

bars and rough bars with the skin on. Messrs. Segundo and Robinson found the rough bars to be somewhat stronger than the planed bars. Mr. Millar found that bars run with hot metal were a very little weaker and deflected a little more than bars run with dull metal.

COEFFICIENT OF BENDING STRENGTH FOR CAST-IRON BARS.

Authority	Dimensions of bars, in inches *b* *d* *l*	No. of tests	Coefficient, *f*, in tons per sq. in.		
			Highest	Lowest	Mean
Fairbairn and Hodgkinson	1 × 1 × 54	270	21·0	12·9	16·3
Woolwich . . .	2 × 2 × 20	564	30·0	6·9	18·9
Millar . .	1 × 2 × 36	1,344	—	—	22·6
,, . . .	1 × 1 × 36	50	—	—	19·6
Stephenson, 1847	—	—	25·6	16·5	—
Turner, 1886 .	—	—	28·3[1]	—	—

For the ordinary test bar, 3 feet span, 2 inches deep, and 1 inch wide, the central breaking weight varies for different qualities of iron from $6\frac{1}{2}$ to 42 cwts. Common iron ought to carry 20 cwts., good iron 30 cwts., and Mr. Turner states that iron carrying 40 cwts. can be produced with tolerable regularity if necessary. The most common tests imposed in specifications vary from 25 to 32 cwts. It is usual to take the average breaking weight of the bars of each cast, as from flaws, cold shots, &c., individual bars vary a good deal. The breaking weight in cwts. of the ordinary test bar is 40/27ths of the coefficient of bending strength.

118. *Resistance of Cast Iron to Shearing.*—The resistance of cast iron to shearing is imperfectly known. Mr. Stoney found a resistance of 8 to 9 tons per sq. in.

[1] Maximum of special series of test bars.

The following results are from a paper by Messrs. Platt and Hayward,[1] the experiments having been made at University College. The cast iron had a tenacity of about 11·4 tons per sq. in. The specimens were about $\frac{3}{4}$ inch in diameter:—

Material	No of tests	Shearing strength, in tons per sq in.
Cast iron, No 1, turned .	13	5·27
,, No. 2, ,,	12	5·18
,, No 2, skin on	7	3·62

It is extremely difficult in shearing experiments to ensure a uniform distribution of stress on the section, and it is possible these values are too low.

119. *Resistance of Cast Iron to Torsion.*—The ordinary expression for resistance to torsion is $T = fZ$; where T is the twisting moment, Z the polar modulus of the section, and f the shearing stress in the most strained layer. For a circular section of diameter d this becomes—

$$T = 0{\cdot}196\, f\, d^3$$

When T is the twisting moment which breaks the bar, this expression becomes an empirical one, and f then has values greater than the real shearing stress, just as in the case of bending. It is better to call the values of f which correspond to the breaking twisting moment coefficients of torsional strength

Experiments by Messrs. Platt and Hayward on the

[1] *Proc. Inst Civil Engineers,* vol xc p 406

same cast iron as that used in their experiments on shear gave the following results. The bars were about $\frac{5}{8}$ inch in diameter. Some Woolwich results on 276 specimens of cast iron 1·8 inch in diameter are also given, and some American results:—

Material	Coefficient of torsional strength f	Coefficient of rigidity C	Authority
	Tons per sq in	Tons per sq in.	
Cast iron, No. 1, turned .	15 9	3,197	Platt and Hayward.
,, ,, skin on .	18·1	3,402	
,, No. 2, turned .	17·1	2,947	
,, ,, skin on .	15·3	3,147	
,, highest . .	22 0	—	Woolwich
,, lowest . .	8 25	—	
,, mean .	13 5	—	
,, highest . .	23 5	—	American
,, lowest . .	12 5	—	

MALLEABLE CAST IRON.

120. Malleable cast iron is obtained by heating castings to red heat in contact with hematite iron ore, for a period varying from some hours to two or three days. The amount of carbon in the cast iron diminishes, and it becomes to a certain extent malleable and capable of being bent or hammered.

The following tests were made by Professor P. C. Ricketts, at the Rensselaer Polytechnic Institute (*Van Nostrand's Magazine*, 1885). The cast iron had a tenacity ranging from 6·5 to 13·1 tons per sq. in., the mean tenacity being 10·1 tons per sq. in. The elastic limit given appears to be the yield point. The extension was measured in series i. in a length of 5 inches;

in the other experiments in a length of 7½ inches, except in experiments 6 to 10, series iv., where it was measured in a length of 10 inches.

TENSILE STRENGTH OF MALLEABLE CAST IRON.

Form of bars		Approximate size	Mean elastic limit, in tons per sq in	Tenacity, in tons per sq in			Elongation per cent	Contraction per cent
				Highest	Lowest	Mean		
Square .	1-8	¾ × ¾	0·45	19·7	16·1	17·8	5·6	6·9
,, .	11-14	,,	1·01	—	—	14·5	2·0	4·7
Rectangular,	1-7	1 × ⅜	1·33	16·5	14·6	15·3	2·4	6·6
Circular .	1-9	½ diam	1·02	19·8	16·1	17·4	3·5	10·0
,, .	1-13	¾ ,,	·65	18·2	12·8	15·2	1·7	1·3
,,	1-8	¾ ,,	—	—	—	13·4[1]	0·8	3·5

Short prisms and cylinders carried loads of from 48 to 71·5 tons per sq. in. before crushing. In bars broken by bending the coefficient of bending strength varied from 20 to 40 tons per sq. in. Martens[2] found the ultimate tensile strength of malleable cast iron to be 16·4 tons per sq. in.; contraction, 8·2 per cent.; extension in 8 inches, 2·5 per cent.; limit of elasticity, about 4·4 tons per sq. in.

[1] Skin turned off

[2] *Mitt. a d K Techn Versuchsanstalt zu Berlin*, 1886, p 131

CHAPTER X.

IRON AND STEEL.

121. *Constituents of Weld Iron.*—Broadly speaking, wrought iron is softer, more ductile, more trustworthy, and more valuable the purer it is. All commercial iron, however, contains some carbon, which renders it harder and stronger, and some other constituents or impurities. Amongst these sulphur, while little affecting its quality when cold, makes it red-short and difficult to roll. Phosphorus has an effect similar to that of carbon, but phosphoric iron is cold-short and treacherous. Other constituents are present in quantities so small that their effect is not well marked.

Constituents of Ingot Iron and Ingot Steel.—It is to the homogeneousness due to the mode of manufacture that these materials probably owe their great ductility as compared with wrought iron. Consequently they will bear, and as commercially manufactured do in fact contain, a greater proportion of those hardening constituents, which add to the strength at the price of some loss of ductility. The purest of them, the low basic steels, of a tenacity of 21 tons per sq. in., are the most ductile. In proportion, generally, as alloying materials

increase, the strength increases and the ductility diminishes. Carbon, manganese, phosphorus, and silicon are all hardening constituents, but, either in consequence of inducing differences of fusibility or differences of density, they are not equally safe constituents of steel. Phosphorus, sulphur, and silicon are dangerous constituents, while manganese and carbon are the most useful and least prejudicial. Carbon may exist in steel in proportions varying from 0·15 to 1·5 per cent., the hardness, strength and capability of tempering increasing as the proportion of carbon is greater. Manganese appears to be necessary in the manufacture of steel. In the fluid metal it reduces the iron oxide, and forms with silica a fluid slag. The manganese which remains acts like carbon in hardening the steel, but less energetically. Perhaps, also, it diminishes the ductility less. Usually steel contains 0·25 to 0·5 per cent. of manganese. Chromium and tungsten have also been used in producing hard and yet ductile steels.

In obtaining steel castings silicon is added in such quantities that the cast metal contains 0·2 to 0·3 per cent. of silicon. To neutralise the prejudicial action of silicon on the stability of the iron-carbon compound, there should be also manganese to an amount exceeding the silicon by one-half.[1]

It is beyond the purpose of the present work to give in detail analyses of wrought iron and steel, but the

[1] Chernoff. *Proc. Inst. of Mech. Eng.*, 1880, p. 174.

following short summary is a guide to the ordinary composition of these materials :—

	Per cent					
	Carbon	Manganese	Silicon	Sulphur	Phosphorus	Iron
Wrought Iron	0 02-0·25	0-0 3	0-0 2	0-0 015	0-0·15	99-99 5
Steel :						
Tyres[1]	24-·63	·21-·52	·16-·33	01-·09	·04- 05	98 74
Rails[1]	·35-·60	·80-1 0	04-·10	07-·14	·03- 07	98 44
Mild Plates[2]	·115	504	·055	·028	·037	99 35
Med.-hard do.[2]	·33	1 008	·065	·022	·075	98·40

122. *Interpretation of Observations in a Tensile Test of Ductile Material.*—For wrought iron and steel the tensile test is the most trustworthy. It is desirable to examine fully what can be deduced from observations taken in a careful tensile test, without considering at present what indications of quality are attended to in ordinary commercial testing. The table on next page gives the observations taken in testing a piece of Lowmoor plate. The direct observations are the loads and corresponding elongations. The final elongation is measured after the bar is broken, and at the same time the area of the fractured section.

The maximum stress is 23·2 tons per sq. in., reckoned on the original area. Beyond this stress local contraction begins, and the load has to be reduced.

All through the test the section is diminishing, and on the principle stated in § 23 the reduced section may

[1] Mr. R. Routledge of the North Eastern Railway Laboratory.
[2] Mr. John Rogerson. *Proc. Inst. of Mech. Eng.*, 1881, p 564

PLATE OF LOWMOOR IRON, No. 142

(Broken with stress in the direction of rolling Section, 1 sq. in. Elongations measured in 8 inches.)

(1) Stress, in tons per sq. in. p	(2) Elongation, in ins λ	(3) Area of section ω_1	(4) Stress per sq. in. of reduced section p_1
17	025	997	17 05
18	14	·933	18 31
19	·20	976	19·47
20	·28	966	20 69
21	·38	955	22 00
22	56	935	23·54
23	90	899	25 59
23 2	1 34	·857	27·08
22 7	[1 65]	[777]	29 20

be calculated. If ω is the section when the length is l, and ω_1 the section when the length is $l + \lambda$, then $\omega\, l = \omega_1 (l + \lambda)$, and

$$\omega_1 = \omega \frac{l}{l+\lambda},$$

and the corresponding real stress at the section is $p_1 = p/\omega_1$.

Columns (3) and (4) give values thus calculated. It will be seen that the real stress increases faster than the nominal stress.

The final measured extension 1·65 consists of an extension 1·34 due to the load of 23·2 tons, and distributed over the 8-inch length, and a further extension, while the load was diminished, in the local contraction. By reversing the equation above, the rate of extension at the section of fracture may be calculated. It is easily seen to be $(\omega - \omega_1)\, l/\omega_1$. This gives for the rate of elongation at the section of fracture 2 29 inches in 8 inches, or 28 per cent., which may be called the

elongation at the contraction.[1] How far these deductions are useful in practically determining the quality of the material remains to be determined. Obviously, however, they represent the actual facts of the test more closely than the usual mode of calculation. For comparison a test of Lowmoor plate crossways of the grain is appended :—

p	λ	ω_1	p_1
16 0	015	·998	16·03
17	·06	·993	17·13
18	·115	·986	18·26
19	·20	·976	19·47
19 7	[·32]	[962]	20 48

The area of fracture corresponds to an elongation of 0·316 inch in 8 inches, which agrees closely with the measured elongation. This shows there was no local contraction.

The following table gives similar calculations for a steel plate :—

MILD STEEL PLATE. Area, 1 sq in.

(Elongations measured in 10 inches)

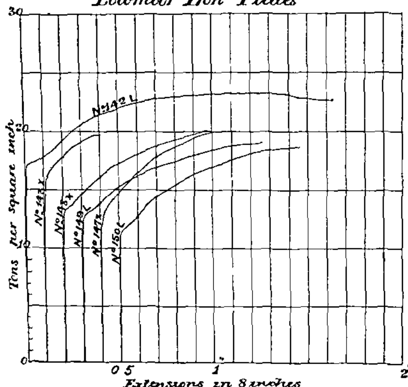
Stress, in tons per sq in. p	Elongation in 10 ins, in ins. λ	Reduced section ω_1	Stress per sq. in. of reduced section p_1
19	·09	·991	19·17
20	·33	968	20 65
21	·40	·962	21 84
22	·49	·954	23 08
23	·56	·947	24 29
24	·70	·935	25 68
25	·87	920	27·17
26	1·20	·893	29 12
26 43	2 15	·823	32·11
25 5	[2 55]	[·576]	44·27

[1] M. Considère proposes to call the elongation up to the maximum load the proportional elongation, and the elongation calculated from the contracted section the elongation due to striction.

The fractured area corresponds to an elongation of 7·3 inches in 10 inches, or 73 per cent. The yield point of this steel was 16·6 tons per sq. in.

123. *Stress at which Local Contraction begins.*—M. Considére[1] has indicated that local contraction must

FIG. 111.



begin when the load on the bar is a maximum. The total load on the actual section is $p_1 \omega_1$, which is increasing so long as maximum load is not reached. Hence, the stress p_1 a given section will carry increases

[1] *L'emploi du fer et de l'acier*, p 22.

Bauschinger's results on Ternitz steel agree well with the formula—

$$T = 27{\cdot}62\ (1 + C^2).$$

M. Deshayes, of Terre Noire, gives the following equations for the tenacity T and elongation in 4 inches, per cent., in terms of the percentage of carbon, manganese, and phosphorus :—

$$T = 19{\cdot}5 + 11{\cdot}4\,C + 30\,C^2 + 11{\cdot}4\,Mn + 9{\cdot}5\,Ph.$$

$$\text{Elongation} = 42 - 36\,C - 5{\cdot}5\,Mn - 6\,Si.$$

Col. Maitland gives for steel used for guns at Woolwich, after oil hardening—

$$T = 140\,C + 20\,Mn - 10.$$

126. *Increase of Strength from Reworking.*—By repeated piling and rolling wrought iron improves in quality; but, if experiments by Mr. Clay, of the Mersey Steel Works, are to be trusted as giving a general law, there is a point beyond which reworking injures the iron. He took some puddled bar and rolled it repeatedly, trying the elongation each time. The following are the results :—

	Tenacity, in tons per sq. in.
Original State	19·6
Second Working	23·5
Third ,,	26·6
Sixth ,, (maximum)	27·5
Ninth ,,	26·0
Twelfth ,,	19·6

Influence of the Amount of Reduction in Rolling on the Strength of Iron Bars.—In the Report of the United States Testing Board, for 1881, data are given showing

that the amount of work put on a bar considerably affects its tenacity and elastic limit. Tests of iron for chain cables showed differences of strength for different diameters, and this led to a special series of experiments, in which bars of the same iron were rolled so that the section of the finished bar had greatly different ratios to the area of the pile from which it was rolled. These bars were very uniformly heated, as it was found that underheating in rolling tended to give an increased tenacity and higher elastic limit, and overheating a reduced tenacity and lower elastic limit.

INFLUENCE ON THE TENACITY AND ELASTIC LIMIT OF THE AMOUNT OF REDUCTION IN THE ROLLS.

IRON BARS.

Size of bar	Area of bar in per cent. of area of pile	Tensile strength, tons per sq. in.		Elastic limit (approximate), tons per sq. in.	
		Rough bar	Core, or bar turned down	Rough bar	Turned bar
4	15·7	—	20·6	—	
3¾	13·8	—	20·8	—	
3½	12·0	—	21·0		
3¼	10·4	—	21·0	—	
3	8·8	—	21·3	—	
2¾	7·4	—	20·7	—	
2½	6·1	21·1	21·1	13·25	1[illegible]
2¼	5·5	21·6	22·0	13·9	14
2	4·4	21·4	21·6	16·0	14
1⅞	7·7	22·2	22·0	15·9	16
1¾	6·7	22·5	21·8	16·1	17
1⅝	5·8	22·5	21·9	15·8	15[illegible]
1½	4·9	22·7	23·1	15·6	16[illegible]
1⅜	4·1	23·6	21·8	17·4	—
1¼	3·4	23·5	22·2	17·6	18·1
1⅛	4·0	22·3	22·5	15·8	16·8
1	3·1	23·1	22·8	17·4	17·2
⅞	4·9	22·6	22·5	15·1	14·8
¾	3·6	22·6	22·4	15·1	16·0
⅝	2·5	23·3	22·9	15·4	15·4
½	2·2	23·3	23·5	17·1	17
⅜	3·7	24·1	24·1	17·2	17
¼	1·6	25·4	25·6	—	

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	Tenacity, in tons per sq. in.
Original State	19·6
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Sixth " (maximum)	27·5
Ninth "	26·0
Twelfth "	19·6

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that the amount of work put on a bar considerably affects its tenacity and elastic limit. Tests of iron for chain cables showed differences of strength for different diameters, and this led to a special series of experiments, in which bars of the same iron were rolled so that the section of the finished bar had greatly different ratios to the area of the pile from which it was rolled. These bars were very uniformly heated, as it was found that underheating in rolling tended to give an increased tenacity and higher elastic limit, and overheating a reduced tenacity and lower elastic limit.

INFLUENCE ON THE TENACITY AND ELASTIC LIMIT OF THE AMOUNT OF REDUCTION IN THE ROLLS

IRON BARS

Size of bar	Area of bar in per cent of area of pile	Tensile strength, tons per sq. in.		Elastic limit (approximate), tons per sq. in.	
		Rough bar	Core, or bar turned down	Rough bar	Turned bar
4	15·7	—	20·6	—	10·45
3¾	13·8	—	20·8	—	10·5
3½	12·0	—	21·0	—	11·1
3¼	10·4	—	21·0	—	11·0
3	8·8	—	21·3	—	11·8
2¾	7·4	—	20·7	—	11·7
2½	6·1	21·1	21·1	13·25	13·3
2¼	5·5	21·6	22·0	13·9	14·3
2	4·4	21·4	21·6	16·0	14·2
1⅞	7·7	22·2	22·0	15·0	16·5
1¾	6·7	22·5	21·8	16·1	17·4
1⅝	5·8	22·5	21·0	15·8	15·2
1½	4·9	22·7	23·1	15·6	16·3
1⅜	4·1	23·6	21·8	17·4	—
1¼	3·4	23·5	22·2	17·6	18·1
1⅛	4·0	22·3	22·5	15·8	16·8
1	3·1	23·1	22·8	17·4	17·2
⅞	4·9	22·6	22·5	15·1	14·8
¾	3·6	22·6	22·4	15·1	16·0
⅝	2·5	23·3	22·9	15·4	15·4
½	2·2	23·3	23·5	17·1	17·4
⅜	3·7	24·1	24·1	17·2	17·9
¼	1·6	25·4	26·6	—	—

It is no doubt due to an analogous difference in the amount of work done on the material in hammering and rolling that large forgings are found to be weaker than small bars, and the interior of large forgings weaker than the exterior. Thus, for instance, a propeller shaft of the U.S. despatch-boat *Dolphin* broke on the trial trip, and test bars cut from the shaft gave the following results :—

—	Elastic limit, tons per sq. in.	Tenacity, tons per sq. in.	Elongation per cent.
From centre of shaft	15·2	24·1	2
From surface of shaft	14·3	35·7	18

Some very interesting tests of wrought iron, cut in different directions from forgings of large size, are given by Mr. Mallet, in a paper on the 'Coefficients of Elasticity and Rupture in Massive Forgings.'[1] Mr. Mallet was engaged in the construction of some 36-inch built-up mortars, and at the same time the Mersey Company were engaged in constructing the first large forged wrought-iron gun. The weakest wrought iron was some cut radially from the end of a heavy cylindrical forging, which had been exposed during forging to heating during about six weeks. Its elastic limit in tension was only $3\frac{1}{4}$ tons, and it broke at $6\frac{3}{4}$ tons per sq. in. Mr. Mallet concluded that the iron of very heavy shafts, forged guns, or cranks may be expected

[1] *Proc. Inst. of Civil Engineers*, vol. xvııı, Session 1858-9. This paper is interesting from containing probably the earliest carefully plotted stress-strain diagrams for tension and pressure.

to have an elastic limit of 7 tons per sq. in., and to break at a tension of 15 tons per sq. in. The following are a few of Mr. Mallet's results :—

Material	Tension, in tons per sq. in.	
	At elastic limit	At fracture
Hammered slab (12″ × 4″)	15.3	24.1
Rolled slab (12″ × 4″)	10.9	23.0
Forged slab (48″ × 48″ × 12″)	8.75	18.6
Mersey gun :—		
Original faggot bars	12.0	21.9
Longitudinal cuts	9.8–10.9	19.7–17.9
Circumferential cuts	6.6–5.5	16.4–16.7
Transverse cut	3.28	6.56
Borings from gun, reforged and rolled into a bar	5.47	22.32

127. *Effect of Quick and Slow Rates of Loading on the Strength of Test Bars.*—Before deciding on the details of the tests of the steel for the East River Bridge, experiments were made to determine whether the strength of the specimens was affected by the rate of loading. Nine test bars of steel, 1 inch square and 24 inches long, were cut from the same rolled bar, and these were used without further preparation. Three test bars were broken in periods of 3 minutes, three in periods of 6 minutes, and three in periods of 20 minutes. No difference in ultimate strength was found which could be attributed to the quicker or slower rate of loading.[1] The influence of time on the elongation has been discussed in § 36. M. Barba has stated that in rapid

[1] Mr. W. Denny appears to have made experiments leading to the same result. See Hackney, 'Forms of Test Pieces,' *Proc. Inst. of Civil Engineers*, vol. lxxvi.

testing the resistance is somewhat greater and the elongation less than in slow testing. But this conclusion is certainly doubtful.

128. *Form and Size of Test Pieces.*—The forms generally adopted for test pieces have been described in § 77. Unfortunately no general agreement has been come to as to the size to be adopted. The ordinary Admiralty test pieces of plates are of the form *d*, Fig. 81, p. 189, and for all thicknesses of plates are of such a width that the section is about 1 sq. in. The extensions are measured in 8 inches. Other engineers adopt a length of 10 inches for measuring the extension, and a constant width of 2 inches for all thicknesses of plates. In the recent German conferences it has been recommended that the standard width for all plate specimens shall be 30 mm. (1·2 inch). and the extension measured in 200 mm. (7·87 inches). The French Admiralty commonly adopt test pieces 30 mm. wide and 200 mm. between gauge points. Undoubtedly plate specimens $1\frac{1}{2}$ or $1\frac{1}{4}$ inch wide, with the extension measured in 8 inches, would be very convenient, and the results would be comparable with the greatest number of earlier English, German, and French results.

For many cases very much shorter test pieces a unavoidably used. Thus in the case of tyres it is necessary, and in that of rails it is convenient, to adopt shorter test pieces. Probably in such cases a diam of $\frac{5}{8}$ inch and a length for extension of 2 inches most convenient size.

The criterion of ductility for practical purposes is either the contraction of area at fracture or the extension between the gauge points. One objection to the contraction of area is the difficulty of measuring it, especially in the more rigid materials; another is the probability that it is considerably affected by local conditions of hardness and homogeneousness at the point of fracture. The extension is less open to these objections, but then the percentage of extension varies with the form and proportions of the test piece. This variation is almost entirely due to the variation of length of the local contraction. If the extension is taken, either (1) up to the maximum load before local contraction begins, or (2) from the broken bar after discarding the contraction in the neighbourhood of the fracture, or (3) deduced from the contracted diameter in parts not near the fracture, the variation of the percentage of extension with different forms and proportions of test bar disappears.[1]

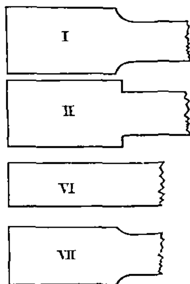
In the discussion on Mr. Hackney's paper the author suggested that the bar should be marked in 1-inch or ½-inch lengths before testing, and the extension measured, omitting the inch or two in which the fracture occurred. In the appendix to the discussion Prof. Styffe made the same proposal.

Professor Kennedy has made experiments on the effect of varying the form of the ends of plate test bars

[1] According to Barba, the extension up to maximum load is rigorously independent of the proportions of the test bar

on the strength and elongation.[1] The most important forms tried are shown in Fig. 115. With soft basic steel, annealed, there was no difference of strength or extensibility distinctly traceable to the form of the ends of the test bar. Even form II broke fairly in the middle, and not at the shoulder. Some pieces of common wrought-iron plate, however, showed marked differences when tested in the forms II and VII. Hard or inferior material seems, therefore, to be affected by the form of the ends.

Fig. 115.



129. *Variation of Quality in Pieces cut from the same Plate.* — Some experiments seem to show a more or less considerable difference of quality in pieces cut from the same plate. No doubt in some of these cases the differences are due to errors in testing. If the testing machine is not itself inaccurate, still imperfect centring of the specimen in the machine, or imperfect gripping of the specimen in the shackles, may give rise to considerable apparent differences of strength. But in other cases there appear to be real differences in the quality of the material, and the limits of such differences are not at present determined. Mr. Baker

[1] *Proc. Inst. of Civil Engineers*, vol. lxxvi.

RESULTS OF TESTS OF TWO STRIPS OF BASIC STEEL, UNANNEALED, AND FOUR STRIPS OF WROUGHT-IRON PLATE—ALL SIMILAR EXCEPT IN FORM OF ENDS (KENNEDY).

(Plates about ⅜ inch thick and 1½ inch wide.)

Form	Limit of elasticity, in tons per sq. in.	Breaking stress, in tons per sq. in.	Extension per cent. in a length (always including fracture) of					Contraction of area, per cent.	—
			10 inches	8 inches	6 inches	4 inches	2 inches		
Basic steel, II .	18·87	28·18	21·8	23·9	27·6	31·7	44·5	51·3	Square corners
" VII .	17·46	29·12	20·8	22·5	25·8	31·5	44·5	51·0	Hollow corners
Means .	18·16	28·65	21·3	23·2	26·7	31·6	44·5	51·2	
Wrought iron, II	15·95	21·40	4·6	4·8	4·7	4·5	5·0	9·3	Square corners
" " II	15·55	23·60	6·4	6·7	6·7	7·2	8·5	11·0	" "
Means	15·75	22·5	5·5	5·7	5·7	5·8	6·7	10·2	
Wrought iron, VII	16·05	24·58	14·0	14·2	15·5	17·2	23·0	21·2	Hollow corners
" " VII .	17·81	25·28	14·0	14·5	15·7	18·0	21·0	18·9	" "
Means	16·93	24·93	14·0	14·4	15·6	17·6	22·0	20·1	

has stated that entire bars, 16 feet long, 10 inches wide, and 1 inch thick, gave an average tenacity of 19 tons per sq. in.; while ordinary test pieces, cut from the same bars, broke at a stress 35 per cent., and even in some cases 75 per cent., higher.[1] An iron plate was cut up in the workshops of the Compagnie des Chemins-de-fer de P. L. M. into 32 test pieces.[2] The strength lengthways varied from 20·32 to 29·21 tons per sq. in., and crossways from 20·32 to 23·50. The stretch varied from 12·5 to 21·5 per cent. lengthways, and from 7·0 to 14·5 per cent. crossways.

HARDENING, TEMPERING, AND ANNEALING

130. If steel containing carbon, manganese, or phosphorus in sufficient quantity is heated to about 1,150° or higher, and then suddenly cooled by plunging into a bath of cold liquid, it becomes harder, stronger, and less plastic. The more of the hardening elements in the steel (up to a certain limit), and the lower the temperature, and the greater the power of absorbing heat in the cooling liquid employed, the greater the hardness produced. Water hardens steel more actively than oil, and pure water has a greater effect than soapy water.

In plunging the heated steel into a cooling liquid the exterior loses heat first, and contracts on the

[1] *Proc. Inst. Civil Engineers*, vol. lxxxi. p. 95.

[2] Lebasteur, *Les Métaux*, p. 194.

interior. There thus result tensions in the exterior, which may exceed the elastic limit and cause permanent stretching or even fracture. Afterwards, the interior cools and contracts. But it is now attached to the stretched exterior, and in turn is put into tension. Thus there may arise in hardening a condition of great internal stress. The cracking and twisting which often occur in hardening are indications of this condition of stress. M. Caron has observed that the volume increases in hardening. M. Considére states that if a hardened bar is cut in two by a parting tool in the direction of its length the pieces become curved, with the concavity on the planed side.[1]

By reheating hardened steel and allowing it to cool slowly, the hardening previously induced is diminished. This is termed tempering, or letting down the temper. If the steel is raised to 1,300° or higher, the whole of the induced hardening disappears, and the process is then termed annealing. In annealing the temperature must be high enough, but should not approach the fusing-point or other changes occur. The cooling must be slower the larger the mass to be annealed, and in the case of large masses requires days or even weeks.

Alternate hardening and annealing alter the steel, somewhat in the same way as mechanical forging.[2] The steel, originally coarsely crystalline, and with

[1] *L'emploi de l'acier*, p 10

[2] Colonel Maitland, R A , 'On the Treatment of Gun Steel.' *Proc. Inst. Civil Engineers*, 1887

Material	Original state		After heating and quenching	
	Tenacity, in tons per sq in	Elongation in 10 inches, per cent.	Tenacity, in tons per sq in.	Elongation in 10 inches, per cent.
Very mild steel	25	24	38	10
Harder mild steel	29	23	43	5
,, steel . .	35	22 [1]	50	0
,, ,, .	35	22	43 [2]	11

The following results are given by Lebasteur on steel from Terre Noire, showing the increased effect of tempering as the carbon increases :—[3]

(The bars were 0 8 inch diameter and 7 9 inches between gauge points. Stress in tons per sq in)

Carbon, per cent	Original state			Hardened in oil			Hardened in water		
	Elastic limit	Breaking stress	Elongation per cent	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.
0 150	11 57	23 11	32 5	20 83	29 72	28 6	19 56	28 83	19 0
0 490	14 61	30 48	24 8	28 32	44 77	12 0	30 48	49 53	2 5
0 709	19 56	43 31	10 0	43 69	68 00	4 0	Broke in tempering		
0 875	20 83	44 39	8 4	57 47	67 31	1 0			
1 050	25·08	54 61	5 2	Broke in tempering					

A corresponding series of tests of steels containing different proportions of manganese was also made, the other constituents of the steel being kept constant.

Manganese, per cent	Original state			Hardened in oil			Hardened in water		
	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.	Elastic limit	Breaking stress	Elongation per cent.
0 521	16 70	32 90	24 5	26 48	48 58	12·0	—	—	—
0 060	19 81	38 80	21 4	41 28	62 87	—	—	—	—
1 305	26 16	48 58	17 4	Cracked in tempering			—	—	—
2 008	30 29	56 20	10 5				—	—	—

[1] In 7 inches, and after annealing. [2] Quenched in soapy water

[3] Lebasteur *Les Métaux*, p 72

A similar series of tests was made with steel containing 0·247 to 0·398 per cent of phosphorus. The action of phosphorus was similar to that of carbon or manganese, but less energetic.

EXPERIMENTS ON THE TENSILE STRENGTH OF STEEL AT THE TERRE NOIRE WORKS[1]

(Diameter of bars, 0·55 inch.)

Material	Percentage of carbon	Stress in tons per sq. in.		[illegible]
		Elastic limit	At Breaking	
Forged steel (containing about ¼ per cent of manganese and a trace of silicon)	15	13·70	22·24	24·0
	49	16 32	30·49	24·0
	·709	19 69	[illegible]	15·0
	·875	21·31	46 16	9·5
The same, after hardening in oil	·15	20 43	28 16	25·6
	49	27 79	43·42	12·0
	709	42 86	66·72	4·0
	875	56 38	66 14	[illegible]
Cast steel, not forged (containing about ¾ per cent of manganese and ¼ per cent of silicon)	287	13 08	27 85	8 6
	459	16 51	26 93	3 0
	750	19 00	40 00	3 5
	875	24 42	40 18	1 5
The same, after hardening in oil and annealing	287	19 69	32 27	24 6
	459	20 87	34 58	19·2
	750	22 30	46 23	14 3
	875	28 66	51 46	3 5

131. *Injurious Effect when Steel is worked at a 'Blue' Heat or Colour Heat.*—It has long been known, in a more or less vague way, that in cooling from a welding heat steel passed through a condition in which it became brittle and dangerous to work. *First*, it should be noted that there is a temperature at which the steel is brittle and little capable of being bent. In 1881 the

[1] *Proc. Inst. of Mech. Engineers*, 1880, p. 182

'All these results,' says Mr. Strohmeyer, 'point unmistakably to the great danger which is incurred if iron or steel is worked at a blue heat. The difference between good iron and mild steel seems to be that iron breaks more easily than steel while being bent, when either hot or cold; that iron suffers more injury than steel by cold working; but, if it has withstood successfully bending when hot, there is little probability of its flying to pieces when cold, as is almost sure to be the case with mild steel.' Mr. Strohmeyer thinks *that there is no foundation in fact for the opinion that* local heating of a plate sets up strains which may cause fracture. But some qualities of steel are considerably injured if made red hot or blue hot and cooled by holding them with one edge in water. The following table gives these results :—

Material	No. of bendings before cracking			
	Medium-hard steel	Mild steel	Very mild steel	Low-moor iron
Unprepared or annealed	21	12½	26	20
Made red hot and quenched in boiling water	21	10	—	—
Made red hot and quenched in cold water	1	10	19	20
Red hot. Edge quenched in water	3	8	25	27
Blue hot. Edge quenched in water	3	6½	19	18½

The following experiments were suggested to the author by Mr. Strohmeyer's paper. A plate of mild 27-ton steel was broken in the testing machine in the

ordinary way. The longer piece after this test was heated to a temperature a little below redness, and while at that temperature it was bent to a shallow curve and straightened again. It was then tested in the ordinary way. The results were these :—

	First test	Second test, after bending while hot
Tenacity .	27·0	32 0
Contraction . .	51 0 per cent	21 0 per cent.

These results seem to show that the tenacity is *increased at the expense of the ductility*. Some test pieces of the same mild steel were heated to red heat, placed on a V block, and quietly bent to an angle of about 15° at each end out of straight. The bending pressure was put on just as the redness disappeared. The test pieces were then straightened in the same way. Lastly, they were tested by tension. Fig. 117 shows the result obtained. In the place which was the middle of the curvature in bending there is scarcely any measurable contraction of area, or extension. On each side of the middle of the bar, where there was hardly any bending, the material is still ductile and draws down The figure shows the widths and thicknesses of the bars. The elongations in each inch length were as follows :—

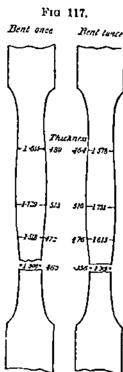


Fig 117.

ELONGATIONS IN EACH INCH

Bar bent once and straightened		Bar bent and straightened twice.	
0·048		0·120	
0·152		0·154	
0·138		0·156	
0·080		0·064	
0·020	Heated part	0·000	Heated part.
0·010		0·002	
0·138		0·082	
0·287		0·174	
0·622	Break.	0·610	Break.
0·100		0·232	
0·100			

In the part heated and worked (by bending) the steel is not weaker but it is stiffer. The bar has been rendered unhomogeneous, and consists of portions of quite different extensibility. It is easy to see that by locally treating a plate in this way it may be rendered extremely treacherous, even without assuming that the heating and bending has created a condition of internal stress.

The results in the following table, obtained by Mr. Webb, at Crewe, carry the same lesson of the gain of strength with the loss of ductility. For convenience of comparison the results for plates bent or hammered at blue heat, and not annealed after, are separated from the others. All were tested cold, except those marked as tested hot.

132. *Hammer Hardening and Cold Rolling.*—It is well known that ductile materials can be rendered more elastic and harder by hammering, planishing, or wire-drawing cold, and this action is identical with that which occurs in mechanical operations in many ways, sometimes with useful, sometimes with prejudicial,

Condition of material	No of tests	Tenacity, in tons per sq in	Elongation in 10 ins p c
Ordinary plate, annealed . .	3	30 96	23 6
Hammered while blue hot and annealed	2	30 26	23 8
Bent while blue hot and annealed	3	30 74	22 1
Bent red hot and cooled .	3	31 65	22 5
Annealed plates bent cold .	3	32 42	12 5
,, ,, and annealed	3	30 60	23 63
Bent three times blue hot	1	38 04	4 3
Hammered while blue hot . .	2	35 24	10 05
Bent once blue hot . .	3	31 95	7 5
Tested while blue hot . .	2	38 80	11 4

results. Whenever a ductile material is subjected to deformation by pressure at temperatures below those at which the metal is plastic, the strength and elastic limit are raised, but the elongation at fracture is diminished. The elasticity is increased, but the plasticity is diminished. The author has noticed that, in very long rail bars, the colder end which passes last through the rolls has a higher yielding point and strength, but less elongation at fracture, than the hotter end. The following are some results from pieces cut from steel rails rolled 150 feet long :—

Test No.	—	Tenacity, in tons per sq. in.	Extension in 2½ inches, per cent	Contraction of area, per cent	Work done per cub in in inch tons up to max. stress
36	Hot end	46·37	22 0	49 17	5 15
37	,,	45 03	26 0	54 63	6 72
38	,,	46 73	22·0	46 85	5 45
40	Cold end	49 84	17·6	33 17	7·07

The work done was measured from an autographic diagram.

Many years ago an American process of cold rolling was introduced. Round bars passed through rolls cold were straightened, polished, and rendered stronger and stiffer. The following experiments by Sir W. Fairbairn on a bar of good Dudley iron show how the mechanical properties of the material were affected by the process :—

Material	Tensile strength tons per sq in	Elongation in 10 ins. per cent.
Rough rolled bar, 1¼ inch diameter, in ordinary state	26 0	20 3
The same, turned down to 1 inch diameter in lathe	26·7	22 4
Bar, cold, rolled to 1 inch in diameter .	35·4	8 0

The strength increased one-third, and the plastic elongation diminished more than one-half.

The following results are given by M. Considére :—[1]

Material	Elastic limit, in tons per sq in.	Tenacity, in tons per sq in.	Elongation, per cent.
Very mild steel in ordinary state	16 07	26 99	26 5
The same, compressed by hydraulic press at 32 tons per sq in.	22 67	28·32	17 0
Ship steel in natural state .	18·80	33 34	18 0
The same, reduced by cold rolling from 10 to 9 45 mm thick	26 92	34 61	11 5
Iron plate, natural state .	14 48	23·75	15 0
The same, reduced by cold rolling from 8 to 7 1 mm thick	26 42	29 78	7 0

[1] *L'emploi du fer et de l'acier*, p. 148.

The gain of ultimate strength is here not large, but the rise of the elastic limit (probably the yield point) is very marked. The diminution of plasticity, shown by the ultimate elongation, is also marked. Wiredrawing is a process similar to cold rolling, and in wiredrawing the increase of strength is very considerable.

The effect produced by hammer hardening or cold rolling is entirely removed by annealing; and doubtless it is to the removal of some effect of this kind, due to rolling at too low a temperature, that the diminution of strength by annealing, which sometimes occurs, is due.

Mr. W. Parker's Experiments.—Mr. W. Parker has recently shown that any mechanical deformation, such as bending, has a similar effect to cold rolling or hammering. In the autographic diagram the yield point disappears, and the true elastic limit is lowered. The following table shows very simply the analogy in the effect of hardening by sudden cooling and hardening by mechanical pressure in the case of very ductile material. Similar bars of Siemens-Martin steel plate, $\frac{3}{4}$ inch thick and 2 inches wide, were taken. No. 1 was tested in its ordinary state. No. 2 was bent cold to a radius of $8\frac{1}{2}$ inches, and straightened. No. 3 was treated similarly at blue heat. No 4 was heated, and quenched in cold water. No. 5 was treated like No. 2, and then annealed. It gave a diagram almost exactly like No. 1.

No. of Test	Tenacity, in tons per sq. in.	Yield point, tons per sq. in.	Elongation in 10 ins., per cent	Contraction of area, per cent.	—
1	27·2	14·9	27·8	53·6	Ordinary state
2	27·75	No yield point	25·7	52·6	Bent cold
3	31·2	"	20·7	50·5	Bent hot
4	32·7	"	17·6	32·0	Quenched·
5	27·1	15·3	29·2	53·5	Annealed

133. *Local Hardening.*—If a plate is sheared or punched a very considerable lateral pressure is exerted on the metal near the cut edge. The action diminishes rapidly from the cut edge towards the interior of the mass, like the stress in a thick cylinder subjected to internal pressure. For about $\frac{1}{8}$ inch from the cut edge the metal is hardened, and its power of extension greatly diminished. M. Barba cut from a punched plate the ring of metal surrounding a punched hole, and found it to be extremely brittle and incapable of bending. M. Considére has shown that a permanent condition of compressive stress is induced in the ring immediately round the hole.

That the diminution of strength of a punched plate is due to the hardening of the metal round the hole is now established. M. Barba showed that rimering out a ring $\frac{1}{8}$ inch thick round the punched hole, or annealing the plate, entirely removed the prejudicial effect of punching. The punching is more injurious the thicker the plate, and this is obviously due to the increase of lateral pressure in punching thick plates. It is less injurious if the die-block hole is larger than the punch, for that diminishes the lateral pressure. Sheared strips of

ductile material are known to be brittle when bent. Mr. Baker has mentioned a case of a steel plate which had been sheared which cracked in several places while being straightened cold.

Some experiments of M. Barba showed that the diminution of strength in a bar in which a hole had been punched (reckoned on the net section) was greater the wider the bar.

Thus, some steel test bars 0·28 inch thick were punched with a hole 0·68 inch in diameter. The normal tenacity of the steel was 32·7 tons per sq. in. The punched bars of different widths gave the following results :—

Width of bars, in inches	1 28	2 0	2 72	3 44	4 16	4 88
Tenacity—cylindrical holes	27 1	25 9	25 3	22 7	24 3	23 1
„ conical holes .	31 7	28 3	26 3	22 4	22 9	23 7

Further experiments have been made by M. Considére on a plate of Siemens-Martin steel, containing 0·34 per cent. of manganese and 0·22 per cent of carbon, and a plate of Bessemer steel, containing 0 38 per cent. of manganese and 0·33 per cent. of carbon. The normal tenacity of these plates was 32·7 and 38·1 tons per sq. in.

M. Considére first verified M. Barba's result, and determined that the increase of strength in the narrow plates was not due to the lateral expansion of the narrow bar under the action of the punch. He then tried bars with a punched semi-hole on each side, leaving

a strip of metal between them. The following were the results :—

Material	Normal tenacity	Tenacity of bar when distance between the holes was, in inches,					
		·2	·24	·32	56	1 2	2 0
Martin steel	32 7	42 6	41·5	40 6	33·3	28 6	27·2
Bessemer steel	38 1	—	—	46·8	39 6	33·6	30 6

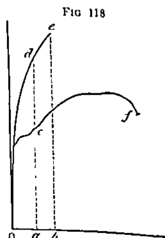
Here a new result appears. When the distance between the holes is less than ½ inch, the punched bar is stronger than the unpunched bar. For wider bars the reverse is the case. Part of the excess of strength in the narrow bars is no doubt due to the suppression of drawing-out, explained in § 33. By tests on plates with drilled holes, M. Considére found that 5 tons increase of strength in the 0·2 inch bar was due to this cause. There remains another 5 tons increase, due directly to the punching. In this very narrow bar the whole of the metal between the holes was hardened by the action of punching, and the increase of strength is that due to cold working. As the bar is made wider it comes to consist of hard metal near the holes, and softer metal, unaffected by punching, between. The heterogeneousness of the material involves unequal distribution of stress. The bar tears at the rigid material, and the tear doubly weakens the bar, partly by loss of section, partly by the unsymmetry which results.

Suppose Fig. 118 represents at $O f$ the normal stress-strain diagram of the material, and at $O e$ the stress-strain diagram for the material hardened by

punching. If the bar stretches an amount O *a*, the stress near the hole will be *a d*, and that of the uninjured material *a c*. The bar *must* tear at the edge of the hole when the strain reaches the value O *b*.

The application of these considerations is far wider and more important than the question of the deterioration of plates by punching. It has been seen that in many ways the plasticity of the material may be altered, so that the yield point disappears and the extensibility is greatly diminished—by rolling at too low a temperature, by sudden cooling, by bending, hammering, cold rolling, or by shearing or punching. So long as such an action is general, the only effect is that a more rigid material is made out of a ductile one. But if, as must often happen, the action is local, then the effect on the strength, like that of the thin ring of hard metal round a punched hole, is far more serious. To know the danger, however, is sufficient. Either local hardening can be avoided, or, if unavoidably produced, it can be destroyed by annealing.

Fig 118



134. *Influence of Temperature on the Strength and Ductility of Iron and Steel.*—The results of experiments on the influence of temperature on the strength and ductility of iron and steel are somewhat discordant. A

maximum strength is reached at 572°, and for higher temperatures decreases rapidly.

Amongst the most careful of the experiments on the effect of temperature are those by Kollmann, at Oberhausen. Three materials were used, the quality of which may be judged from the following summary of the properties when tested at ordinary temperature :—

Material	Tenacity, in tons per sq. in.	Stress at elastic limit, in tons per sq. in.	Elongation, per cent.
Fibrous iron . .	23·5	17·1	17 5
Fine-grained iron	25 4	17 4	20·0
Bessemer steel .	37 8	24 5	14·5

These experiments show a regular decrease of strength with increase of temperature in all cases. The following table, calculated by Roelker,[1] gives the strength at different temperatures in terms of the strength at ordinary temperatures. For comparison the results of some experiments made by the Franklin Institute are added :—

Temperature. Fahr	Fibrous wrought iron	Fine-grained iron	Bessemer steel	Wrought iron, Franklin Institute
0°	100	100	100	96
100	100	100	100	102
300	97	100	100	106
500	92 5	98 5	98 5	104
700	81 5	90	68	92 5
1,000	26	36	31	36
1,500	10	15 5	12	—
2,000	3 5	5	5	—

Mr. Barnaby made some experiments on iron and steel for the Admiralty, and these experiments are

[1] *Proc Inst. Civil Engineers*, vol. lxvii. p 437.

important, both as being recent and made on test bars of reasonably large size. The bars were partly heated in oil, partly in sand; generally, however, they were taken out of the hot bath and broken as quickly as possible. The temperature was judged from the colour of the fractured surface, or in some cases by observing whether tin or lead melted when placed in contact with the bars.

EXPERIMENTS ON THE INFLUENCE OF TEMPERATURE ON THE STRENGTH AND ELONGATION OF IRON AND STEEL BY MR BARNABY

(Elongations in 8 inches)

—	Temperature, Fahr.	Tenacity, tons per sq in.	Elongation, per cent
BB Boiler iron lengthways	60°	23·93	23 95
	450	27 08	8 38
	490	27 4	12 5
	60	22 39	13 28
	500	27 15	10 93
	530	26 3	10 15
The same across fibre	60	21 75	9 3
	450	24 6	6 24
	490	22 6	3 12
Bowling iron	60	21 1	15 62
	490	24 4	12 5
	500	23 2	9 37
	550	27 6	17 18
	850 to 900	19·3	18 75
	60	24 8	23 43
	420	30 3	21 87

—	Temperature Fahr	Tenacity, tons per sq in	Elongation, per cent
Bessemer plate	60°	26 07	27 34
	450	40 5	14 06
	520	38 7	17 18
	880	24 02	26 56
Siemens-Martin plate	60	29 10	25 78
	430	33 45	14 06
	490	34 5	18 75
	610	28 0	18 7
	630	30 83	18 74
Bessemer plate	60	28 49	21 87
	430	38 4	18 75
	550	33 08	17 18
	580	18 56	25 0

COLLECTED TABLES OF TESTS OF IRON AND STEEL.

135. In giving tables of the results of tests of iron and steel, the object has been to select some of the most

is probable that, from the great length in which the elongations and compressions were measured, and from the use of two symmetrical verniers, eliminating to a great extent the effect of initial bending, the measurements in these experiments were very trustworthy. One important result of this mode of experimenting was the observation, in a clearer way than previously, of the remarkable behaviour of ductile bars at the yielding point or breaking-down point.

The Committee arrived at the following important conclusion from these experiments :—

'It would appear from these experiments that within the yielding point of steel the amount of lengthening from tension, or shortening from compression, produced by equal forces per unit of area, is nearly the same, and also that the amount is rather less with steel than with wrought iron.'

The experiments show also that the stress at which the material yields or breaks down is nearly the same for tension and compression.

There are two other points very worthy of notice. The first is the great uniformity of mechanical properties within the elastic limit for all the bars, however diverse their mode of manufacture. The other is the much greater uniformity of the results of different tests of the same material than in the more ordinary tests of very short bars.

The compression and extension per ton per inch given in the tables are the mean values before yielding began.

TABLE II. TENSION AND COMPRESSION OF STEEL BARS (STEEL COMMITTEE)

(1½ inch diameter Measurements of extension and compression made on a length of 10 feet)

Mark	Make	*Intended use*	Tension: *Mean extension per ton per inch*	Tension: Yielding stress, in tons per sq in	Tension: Ultimate stress, in tons per sq in.	Contraction of *area*, per cent.	Ultimate elongation per cent in 120 inches	Compression: Mean compression per ton per inch	Compression: Yielding stress, in tons per sq in.
S C	Crucible cast steel	—	000075	26 50	53 74			000073	26·50
S C	,, ,,	—	000075	26 50	53 33	5·7	5 29	000073	26 00
S C	,, ,,	—	000075	25 00	51 21			000073	26·50
N B	,, ,,	—	000076	26 00	52 30			000074	26 50
N B	,, ,,	—	000075	24 50	46 00	20 0	7 29	000076	27 00
N B	,, ,,	—	000076	26 00	54 74			000075	25 00
16	Cast steel	tyres	*000076*	26 00	43 48	5 2	4 74	000071	25 50
H O	,,	piston rods	000076	27 00	41 85	0 0	1 12	000074	26 00
A	Crucible steel	—	000077	20 50	40 54	4 1	4 13	000076	18 00
◇◇	,, ,,	gun barrels	000079	17 00	38 14			000077	16 50
◇◇	,, ,,	,,	000078	17 00	39 61	4 3	7 95	000076	16 00
◇◇	,, ,,	,,	*000077*	*16 50*	*37 79*			*000076*	16 00
K A	,, ,,	—	000077	25 00	37 05	1 5	13 54	000074	24 00
A A	,, ,,	—	000075	20 00	35 47	48 7	9 63	000071	19 50
K	Bessemer steel	—	000077	19 50	35 61			000073	17 00
K	,, ,,	—	000076	19 50	35 26	44 2	11 13	000074	18 50
K	,, ,,	—	000077	19 50	35 34			000073	18 50
31	Cast steel	piston rods	000076	26 75	33 65	1 3	0 89	000073	27 00
K B	Crucible cast steel	rolled	000077	20 50	34 44	2 9	2 02	000074	24 00
H	Bessemer steel	—	000075	19 50	34 09			000076	22 00
H	,, ,,	—	000075	19 50	34 16	45 6	11 90	000076	20 50
H	,, ,,	—	000074	21 00	34 33			000076	21 00
S L W	,, ,,	—	000077	18 00	34 30	19 2	11 48	000076	17 00
S L W	,, ,,	—	000078	17 00	33 07			000074	15 00
◇	,, ,,	tyres and axles	000076	17 50	33 27			000076	16 00
◇	,, ,,	,,	*·000078*	*16·00*	*34 05*	41 2	13 61	*000076*	*15 50*
◇	,, ,,	,,	000079	16 00	33 66			000077	16 00

Y

TABLE III. TENSION AND COMPRESSION OF IRON BARS (STEEL COMMITTEE).

(1½ inch in diameter Extensions and compressions measured on a 10-foot length of bar)

Mark	Make	Use	Tension: Mean extension per ton per inch	Tension: Yielding stress, in tons per sq in	Tension: Ultimate stress, in tons per sq in	Contraction of area per cent	Elongation in 120 inches, per cent.	Compression: Mean compression per ton per inch	Compression: Yielding stress, in tons per sq in
L S	Lowmoor	—	000076	14 00	27 80			000074	13 50
L S	,,	—	·000076	14 00	29 33	5 9	7 01	000075	13 50
L S	,,	—	000077	14 00	29 33			000075	13 00
L	,,	—	·000078	11 00	24 60			000077	12 50
L	,,	—	000078	12 50	25·72	48·8	12 65	000077	10 50
L	,,	—	000078	12 00	24 07			·000079	11 50
K C	Yorkshire	—	000078	13 00	23 62			000076	13 00
K C	,,	—	000078	13 00	24·16	51 4	17 87	000076	13 00
K C	,,	—	·000080	13 50	23·29			000077	—
F R	S C. ✿	—	000083	11 50	22·48			000079	11·50
F R	,,	—	·000081	11 50	22 48	47·7	17 50	000080	11·50
F R	,,	—	000078	12 50	22 92			000082	12 00

137. *Board of Trade Experiments on Iron and Steel.*[1] —The plates were furnished by the Steel Company of Scotland, as material suitable for ships and boilers. The following table gives the mean results of tensile tests of plates of different thicknesses. The elastic limit recorded is properly the yielding stress. The plates were tested lengthways and across the direction of rolling, but in mild steel no sensible difference is found in the strength, and only a small difference in elongation and contraction. The large contraction of area of the steel plates indicates great ductility, and in this respect steel compares favourably with iron. With regard to the iron plates, the boiler plates are more uniform than the ship plates, and contract and extend more before fracture.

[1] Memorandum issued by the Board of Trade upon the Use of Mild Steel, 1881

TABLE IV. TENSILE STRENGTH OF IRON AND MILD-STEEL PLATES ('BOARD OF TRADE REPORT,' 1881).

Thickness of plates, in inches	Direction of stress	Stress at yield point, in tons per sq in.	Tenacity, in tons per sq in.	Elongation in 10 inches, per cent.	Contraction, per cent.
			STEEL PLATES		
1/4	∥	19 0	31 0	23 5	46 0
1/4	+	19 1	31 4	21 2	39 9
1/2	∥	15 8	28 9	29 8	53·2
1/2	+	15 7	28 6	28 9	40 9
3/4	∥	15 8	29 5	29 2	46 8
3/4	+	15 6	29 1	26 6	38 3
1	∥	14 9	28 0	30 6	50·4
1	+	14 8	28 0	25 6	42·4
Means	∥	16 3	29 3	28 2	49 1
Means	+	16 3	29 2	25 5	40 3
			IRON SHIP PLATES		
1/4	∥	—	24 00	7·0	6 8
1/2	∥	—	22 62	6 7	4·7
3/4	∥	—	19 42	3·6	4 8
Means	∥	—	22 01	5·7	5 4
			IRON BOILER PLATES		
1/2	∥	—	21 20	9 0	12 91
1/2	+	—	19 03	2·7	4 28
3/4	∥	—	21 40	10 1	13 30
3/4	+	—	18 67	3 8	5 08
1	∥	—	20 86	9 8	13 00
1	+	—	17·74	3 1	3 87
Means	∥	—	21·15	9·6	13·07
Means	+	—	18 48	3 2	4·41

Tests of Iron Plates by Dr. Bohme.[1]—Table V. contains a very complete series of tests of material, chiefly for boilers, made on similar test pieces. They are chosen partly because the measurements were made with great care.

[1] *Mitth aus den K Techn Versuchs-Anstalten zu Berlin.* 1884.

TABLE V. TESTS OF IRON BOILER PLATES (BOHME)

(The test bars were 2¼ inches wide, and ⅜ to $\frac{7}{8}$ inch thick)

—	Thickness, in inches	Stress, in tons per sq in., at yield point	Stress, in tons per sq in., at maximum load	Elongation, per cent., in 8 inches	Elongation, per cent., in 4 inches	Contraction of area, per cent.
			Tests in direction of rolling			
1 Boiler plate	563	14 10	24 03	20 8	—	28 1
2 ,,	559	15 62	26 42	20 8	—	22 3
3 ,,	520	14 08	21 60	15 7	—	21 7
4 ,,	508	16 15	25 35	19 0		29·7
5 ,,	516	17 14	27 54	21 5		31 1
6 ,,	516	17 00	25 11	17 3	—	23·8
7 ,,	543	13 64	23 54	29 3	33 6	35·4
8 ,,	539	14 21	23 97	29 6	33 9	33·2
9 ,,	520	13 70	23 35	24 3	26 9	28 0
10 ,,	386	14 27	21 95	—	—	—
11	406	13 70	22 83	25·7	29·4	29 5
12 ,,	398	13 83	22 65	22 5	25 6	—
13 ,,	461	14 52	24 10	21 4	23 6	21 0
14 ,,	461	13 90	22 84	15 4	—	—
15 ,,	445	14 08	22 57	17 7	19 2	22 2
16 ,,	449	16 68	26 04	—	21 0	—
17 ,,	455	15 72	24 05	—	24 2	25 7
18 ,,	465	16 00	23 38	—	15·2	—
19 ,,	465	15 66	24 18	—	25 1	20·7
20 ,,	425	17 82	27 35	—	23 3	15 0
21 ,,	465	15 82	23 75	—	24 2	33·4
$\frac{7}{16}$ Ship plate	315	11 95	21 45	5 6	6 4	—
$\frac{7}{16}$,,	315	13 20	24 93	11 4	12 6	17 0
½ ,,	472	15 22	21 75	7 2	7 5	6·4
½ ,,	472	15 60	21 75	5 7	6·4	6 6
½ ,,	472	15 40	23 60	9 6	8 8	—
$\frac{7}{16}$,,	394	15 66	24 23	5 7	6 2	4·0
⅝ ,,	295	15 40	22 95	6 9	7 3	5 3
29 Harkort	532	18 14	22 90	19 3	25 0	40 2
30 ,,	521	17 70	22 83	21 3	27 9	45·1
31 Wohlert	516	13 76	26 95	21 3	27·8	33 4
32 ,,	557	16 18	25 25	18 7	23·4	29 0
33 ,,	569	16 36	26 40	18 7	24 2	22·9
34 Boiler plate	500	16 06	24 74	—	—	—
35 ,,	413	14 50	23 00	11 0	13 7	14 9
36 ,,	394	17 44	25 80	19 3	22 6	19 6
37 ,,	413	15 75	25 35	16 1	17 8	17·7
38 ,,	398	14 78	24 35	—	25 5	27 6
39 ,,	·433	15 60	25 05	—	25·1	30 2
40 ,,	421	17 70	25 57	—	25 3	24 9
41 ,,	413	14·46	25 57	—	28 2	32 9
42 ,,	449	18·20	25·70	24·3	28 6	29 1
43 ,,	480	16 50	24·55	27 0	33·4	34 0
44 ,,	·476	16 18	24 48	25 4	28 2	30 6

TESTS OF IRON BOILER PLATES—*continued*

—	Thickness, in inches	Stress, in tons per sq. in., at yield point	Stress, in tons per sq. in., at maximum load	Elongation, per cent., in 8 inches	Elongation, per cent., in 4 inches	Contraction of area, per cent
45 Boiler plate	·464	17·56	25·40	24·2	29·1	29·2
46 ,,	·472	14·46	24·23	23·5	30·9	31·5
47 ,,	·457	15·15	25·05	22·7	27·6	27·6
48 ,,	·464	15·40	25·45	23·9	29·8	30·8
49 ,,	·469	16·00	25·55	23·9	28·8	31·7
50 ,,	·469	14·84	25·50	23·4	28·2	30·8
51 ,,	·469	15·53	25·25	22·1	26·5	27·8
Tested across the direction of rolling						
1 Boiler plate (Nos 7-9 above)	·524	13·00	20·36	8·8	10·2	16·8
2 ,,	·524	13·06	21·75	12·8	15·9	15·1
3 ,,	·527	12·94	19·46	—	—	—
4 Boiler plate (Nos 10-11 above)	·394	13·45	20·16	8·4	9·4	—
5 ,,	·394	14·08	19·84	7·8	8·2	9·6
6 ,,	·394	14·46	21·82	—	—	—
7 Boiler plate (Nos 13-15 above)	·464	13·76	21·05	7·2	8·4	—
8 ,,	·464	13·35	20·18	7·4	7·6	10·2
9 ,,	·409	15·02	21·25	15·2	17·0	14·9
$\frac{7}{16}$ Iron plate	·315	14·33	21·95	7·4	7·6	—
$\frac{7}{16}$,,	·315	15·34	23·27	6·8	7·7	10·2
$\frac{1}{2}$,,	·472	15·34	20·42	4·4	5·0	1·7
$\frac{7}{16}$,,	·394	14·70	22·82	7·1	7·5	6·1

TABLE VI TENSILE STRENGTH OF BASIC STEEL (GILLOT, 'PROC. INST. C E,' LXXVII P 304)

Description	Section of ingot	Section of test piece, in inches	Tenacity, in tons per sq in	Elongation, per cent, in 10 inches	Elongation, per cent, in 8 inches	Elongation, per cent, in 2 inches	Contraction per cent.
Plate	12″ × 12″	2·015 × ·46	25·89	25·0	27·5	53·1	55·8
Axle	15″ × 15″	1″ diam.	22·29	31·3	34·1	53·1	62·9
Plate	12″ × 12″	2·03 × ·37	24·96	35·0	37·5	62·5	62·7
,,	15″ × 15″	1·99 × ·755	23·00	30·0	31·3	62·5	63·5
,,	15″ × 15″	2·035 × ·59	24·16	27·5	30·5	—	56·5
,,	19″ × 19″	1·52 × ·68	23·92	28·1	34·2	59·4	58·3
Billet from axle	19″ × 19″	1″ diam.	25·98	24·4	26·6	40·6	50·0
Plate	19″ × 19″	1·765 × ·69	26·68	23·8	25·0	43·8	46·6
,,	27″ × 12″	1·52 × ·705	26·68	26·3	28·5	53·1	49·8
,,	19″ × 19″	2·0 × ·505	24·07	28·8	31·3	50·0	48·9
Means	—	—	24·76	28·0	30·6	53·1	55·5

TABLE VII KENNEDY'S TESTS OF LANDORE SIEMENS STEEL.

Description of plates	Limit of elasticity, in tons per sq in.	Tenacity, in tons per sq. in	Elongation in 10 inches, per cent.
⅜ inch plates, suitable for furnaces (along fibre)	17 6	29·33	23 2
⅜ inch similar plates (along fibre)	14 92	27 27	27·2
,, ,, ,, (across fibre)	14 84	26 93	22 3
Rivet steel .	20 65	29 12	21·4

TABLE VIII. TESTS OF STEEL PLATES, ANNEALED AND UNANNEALED.

Description of plates	Tenacity, in tons per sq in	Elongation in 8 inches, per cent.
¼ inch plate, hard steel, unannealed	32 97	16 65
,, ,, annealed	28 52	24 12
¼ inch plate, mild steel, unannealed	26 60	24·32
,, ,, annealed	24 05	29 87
½ inch plate, mild steel, unannealed	28 55	25 05
,, ,, annealed	26 95	26 90
1$\frac{3}{16}$ inch steel boiler plate, unannealed	28 25	21 25 [1]
,, ,, annealed .	25 75	28·75 [1]

The results on ¼ inch and ½ inch plates are given by Mr. W. Denny; that on the thick plate by Mr. Traill.

138. *The Testing of Rails.*—The testing of rails is of very great importance, from the extent of the manufacture, and the serious consequences which may follow the use of unsuitable material. The ordinary tensile test so trustworthy for ordinary materials of construction, is comparatively useless, sometimes even misleading, as a guide to the quality of rails. For rails two requirements have to be attended to, which are to a great extent antagonistic. The rail must be strong and tough, for it has to carry great weights, and suffers

[1] Elongation in 10 inches

severe shocks. But it also must be hard enough to resist abrasion or lamination on the surface. The earlier tests adopted aimed chiefly at securing toughness, and led to the introduction of rails too soft to stand the wear of traffic.

Tests of Rails.—The following table contains tests of 30 steel rails, after use on the Furness Railway for eight years ('Proc. I. C. E.' vol. xlii. p. 74), and of 36 mean values of tests taken weekly during the years 1869–70 ('Proc. I. C. E.' vol. xxx.) :—

TABLE IX TENSILE STRENGTH OF STEEL FOR RAILS.

—	—	Tenacity, in tons per sq in.	Elongation in 2 inches, per cent
Furness rails (Smith)	Maximum	50.4	37.5
	Minimum	30.1	3.0
	Mean	35.4	29.5
Means given by Berkley	Maximum	45.5	—
	Minimum	33.8	—
	Mean	40.5	—

No convenient direct test of hardness suitable for rails has as yet been found. Indirectly, the bending test gives indications of the hardness of the rail. A rail which will carry a heavy load with a high elastic limit in bending is likely to be a hard rail. But if the rail is too hard it is brittle. To control the bending test a falling-weight test has been used. A monkey, or ball, weighing 300, 600, or 1,000 lbs., and falling 6, 12, or more feet on the rail, bends it more or less; the number of blows the rail will stand before twisting or breaking, or the deflection with one blow, is taken as an index of its toughness.

Without attempting any complete account of rail testing, the following suggestions, taken from Mr. Sandberg's paper,[1] may be made. Mr. Sandberg advises (1) that the bending test should be severe, but that no maximum of deflection should be stipulated for—the rail should be required to carry a certain load without sensible permanent deflection; (2) the falling-weight tests should be regulated according to the weight of the rail. The table below, prepared by Mr. Sandberg, gives the tests he proposes, and the ordinary deflections observed.

TABLE X PROPOSED TESTS FOR RAILS

(Distance of bearings, 3 feet for all tests Deflection and set measured on a 6-feet length of rail In the bending test, the load A applied at the centre should produce no permanent set Deflection means temporary deflection)

Weight of rail, lbs per yard	Bending tests					Impact tests			
	A Load, in tons	Usual deflection, in inches	B Load, in tons	Usual deflection, in inches	Usual set, in inches	Weight of ball, cwts	Height of fall, feet	Constant, C	Usual deflection, in inches
33	5	0 125	11	$\frac{3}{8}$-$\frac{3}{4}$	$\frac{1}{8}$-$\frac{1}{2}$	10	6	2 0	2-4
35	6	,,	13	$\frac{1}{4}$-$\frac{3}{4}$	$\frac{1}{8}$-$\frac{1}{2}$	,,	7	,,	,,
40	8	,,	18	$\frac{3}{8}$-1	$\frac{1}{8}$-$\frac{3}{4}$	,,	8	,,	,,
45	10	,,	22	$\frac{1}{2}$ 1	$\frac{3}{8}$-$\frac{3}{4}$	,,	9	,,	,,
50	12	,,	25	$\frac{1}{2}$-1$\frac{1}{4}$	$\frac{3}{8}$-1	20	5	,,	,,
56	14	,,	26	$\frac{3}{4}$ 2	$\frac{1}{2}$-1$\frac{3}{4}$	,,	7	2 5	,,
60	16	,,	32	$\frac{5}{8}$-1$\frac{3}{4}$	$\frac{5}{8}$-1$\frac{1}{2}$	,,	9	3 0	,,
65	18	,,	35	$\frac{1}{2}$-1$\frac{1}{2}$	$\frac{5}{8}$-1$\frac{3}{4}$	,,	11	3 3	,,
70	20	,,	41	,,	,,	,	13	3 7	,,
75	22	,,	43	,,	,,	,,	15	4 0	,,
80	23	,,	45	,,	,,	,,	17	4 2	,,
85	24	,,	48	,,	,,	,,	19	4·4	,,
90	26	,,	50	,,	,,	,,	21	4 5	,,
95	28	,,	51	,,	,,	,,	23	4 8	,,
100	30	,,	52	,,	,,	,,	25	5 0	,,

[1] *Proc Inst of Civil Engineers*, vol. lxxxiv., p 387.

and IV, fibrous; in the directions V and VI, irregularly torn. The following are the mean values obtained:—

TABLE XII. SHEARING RESISTANCE OF IRON AND STEEL (BAUSCHINGER).

Description of plates	Shearing resistance, in tons per sq in., in the directions					
	I	II	III	IV	V	VI
Iron:						
Plates from exploded boiler at Augsburg	16 50	16 64	18 91	19 80	8·46	8 44
Puddled plate (Leon Magis & Co)	17·18	16 25	20 20	19·10	10 30	10 33
Puddled plate (Leon Magis & Co) annealed	18 36	17·84	19 68	19 68	8 89	9 20
Charcoal plate	17 78	17 50	20 16	20 00	9·20	8 06
German Lowmoor plate	18 64	17 60	22 05	21 95	10 05	9 17
Rolled iron bar	22 15	17·16	22 55	19 00	11·70	10 15
Rolled iron bar, annealed	21 20	19 68	23 23	20 25	10 00	13 27
Plates from exploded boiler at Wurtzburg, from uninjured plate	15 42	15·06	17 62	17 68	6 95	7 23
Plates from exploded boiler at Wurtzburg, from injured plate	14 40	14·38	17 26	16 28	5·20	4 76
New locomotive plate	16 00	16 38	19 10	19 90	10 01	9 58
Cast steel:						
Bessemer plate	24·12	23 42	26 45	27·35	22 90	21·45
,, ,,	26 30	26·40	29 20	29 20	25 05	25 70

The resistance of steel in different directions is much more uniform than that of iron.

The following are mean values of torsional tests, made by Messrs. Platt and Hayward at the engineering laboratory of University College.[1] For comparison, values of the tenacity and shearing strength from direct experiments on tension and shearing of the same materials are also given:—

[1] *Proc. Inst. Civil Engineers*, vol xc p. 382

TABLE XIII. TORSIONAL STRENGTH OF IRON AND STEEL (PLATT AND HAYWARD)

Material	Limit of elasticity, in tons per sq. in.	Calculated shearing stress at fracture, in tons per sq. in.	Final twist in revolutions in 9-inch length	Coefficient of rigidity, in tons per sq. in.	Tenacity, in tons per sq. in.	Ultimate shearing stress, from shearing tests, in tons per sq. in.
Wrought iron, Crown best	8·40	25·2	8·90	5,714	21·00	18·76
Bessemer steel	20·28	44·64	3·84	5,750	52·20	35·21
Crucible steel	19·36	42·30	4·36	6,008	52·16	33·20
Landore rivet steel, 0·18 carbon, 0·6 manganese	10·20	29·85	7·85	5,831	28·40	23·00
Crown rivet iron	10·36	28·87	6·00	6,116	25·01	21·21
Steel cut from casting	10·40	34·7	4·15	5,822	38·04	27·00
Siemens-Martin steel	10·16	28·13	9·92	5,981	25·75	20·94
Wrought iron, S C Crown	10·22	29·5	7·45	6,213	24·56	20·75

The apparently high shearing stress in the torsion experiments is no doubt due to the false assumptions involved in the formula for torsional resistance when applied to stresses at rupture.

STEEL CASTINGS

140. Steel castings are now largely used, sometimes in place of cast iron, and sometimes instead of forgings. Roughly, they are usually assumed to have nearly double the strength of cast iron. Tests, however, show wide divergence in the quality of different specimens, both as to strength and ductility. The steel melts at about 3,500° Fahr., a temperature much higher than that of cast iron. Consequently, the contraction of the castings is nearly double that of cast iron. To obviate danger

Some very complete experiments on steel castings, obtained from the manufacturers in America, were made by Mr. A. V. Abbott.[1] The tests were made on the test bars as taken from the sand without removing the skin. The dimensions of the test bars were as follows :—

For tension, $1\frac{1}{2}$ inch diameter, 10 inches between gauge points. For pressure, 2 inches square and $2\frac{1}{4}$ feet long. For bending, 2 inches square, 2 feet long ; loaded at the centre. The average tensile elastic limit was 13·1 tons per sq. in., and the elongation in 10 inches 9 per cent. The mean coefficient of elasticity was 10,900 tons per sq. in.

TABLL XVI. STEEL CASTINGS

No. of sample	Elastic limit in tension, tons per sq. in.	Breaking stress in tension, tons per sq. in	Elongation, per cent, in 10 ins.	Elastic limit in compression, tons per sq in.	Elastic limit for transverse stress, lbs.	Transverse breaking load, in lbs.	Deflection, in inches
1	12 9	19 5	6 0	15 6	6,000	8,000	·72
2	11 4	16 5	0 4	14 0	2,500	3.870	45
2	11 4	18 9	0 8	—	2,600	3,930	·52
3	10 3	19 7	6 0	10 9	3,000	4,181	·88
4	9 5	17 1	10 0	11·9	3,950	5,720	15
6	13 9	20 6	2 0	13 2	4,000	6,259	60
7	16 0	25 3	10 0	16·1	4,000	5,480	20
9	15 8	23·3	9 0	12 0	4,000	6,810	·21
9A	17·0	28·2	29 9	—	—	—	—
9A	17 0	28 0	20 5	—	—	—	—
10	7 8	15·4	8 0	9 1	—	4,010	35

Some experiments by the author on steel castings, turned to ordinary test bars about 1 inch in diameter, gave less favourable results, as shown in table XVII.

[1] *Proc. Inst of Civil Engineers*, vol lxxxiii, p 512

below. Fig. 120 gives autographic diagrams for some of these bars.

Fig. 120

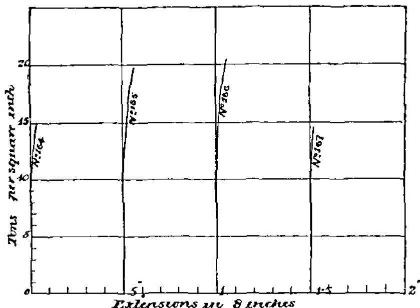


Table XVII Tests of Steel Castings.

Test No	Diameter, in inches	Tenacity, tons per sq in.	Extension, per cent., in 10 ins.	Extension, per cent., in 8 ins.	Contraction of area, per cent.	Coefficient of elasticity, tons per sq in.
162	·997	16 26	0 61	—	0 76	10,930
163	·997	13 05	0 30	—	0 38	14,050
164	·620	15 07	—	0 37	0 60	9,138
165	615	19 86	0·68	—	—	9,972
166	·619	20 53	—	0·75	—	10,220
167	·621	14 52	—	0 25	—	8,384

There were flaws in the fractured sections of 163, 164, and 166

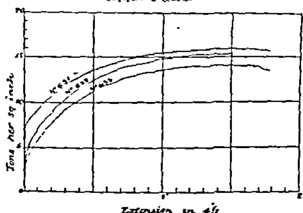
Mitis Castings.—These are castings of wrought iron to which about 0·05 to 0·1 per cent. of aluminium has

Description of material	Tenacity, in tons per sq in.	Authority
Cast copper	8 5 to 11·2	Anderson
Forged copper	15·2	,,
,, 0 015 phosphorus . .	17·0	,,
,, ·02 ,, . .	20 1	,,
,, ·03 ,, . .	21 4	,,
,, 01 ,, . .	22 3	,,
Ingot copper . .	11·6 to 13·3	Thurston
Cast copper	6 5 to 9 2	,,
Rolled copper[1]	12 9 to 14 3	Bauschinger
Rolled copper, ½ inch thick[2] . . .	13 3 to 14·2	Unwin
Hard copper wire	26 0	Wertheim
Annealed ,, ...	20·0	,,

tons per sq. in. for cast copper, and reaches 26·7 for rolled copper (Thurston).

Fig. 121 gives autographic diagrams for copper. The highest diagram is a normal diagram for rolled

Fig 121



copper. The other diagrams are for the same copper, heated, and allowed to cool.

[1] Contraction of area, 30 to 45 per cent.

[2] Extension in 8 inches, 20 to 43 per cent.; mean, 37 per cent.

Tin is chiefly valuable in engineering for alloying with copper to form bronze. Its density is 7·3 to 7·4 (weight, about 456 lbs. per c. ft.). Thurston gives its tenacity as ranging from 0·89 to 2·68 tons per sq. in., and its coefficient of elasticity as ranging up to 3,125 tons per sq. in.

142. *Zinc*, known also as spelter, is used for alloying with copper to form brass. It is malleable within narrow limits of temperature, and can be rolled into sheets for roofing. It fuses at 750° to 930°. Clean *iron immersed in melted zinc gets a protective coating*, the process being termed galvanising. The zinc being electro-positive protects the iron from oxidation, and its own oxide is insoluble in water. If, however, sulphuric acid is present, a sulphate is formed, and the zinc coating perishes. The tenacity of cast bars is 2·0 to 2·9 tons per sq. in. (Thurston). The author found a tenacity of 1·1 to 1·5 tons per sq. in. Cast zinc breaks without sensible elongation or contraction. Trautwine gives for sheet zinc a tenacity of 7·14 tons per sq. in., and for wire 9·8 tons per sq. in. Wertheim gives the coefficient of elasticity as 5,360.

Lead is a very valuable metal for certain purposes from its great ductility. Its density is 11·4 (711 lbs. per c. ft.). It fuses at 620° Fahr. In testing it contracts in section very much. Its tenacity is about 1·1 ton per sq. in., reckoned on the original area of the bar.

143. *Alloys.*— The most complete and extensive

investigation of the properties of alloys is that made by Professor Thurston, for the United States Testing Board.[1] Only a very brief account of the most useful alloys can be given here. As to the general properties of an alloy Professor Thurston says, 'The physical properties of an alloy are often quite different from those of its constituent metals. In most cases, however, the hardness, tenacity, and fusibility will be greater than the mean of the same properties in the constituents, and sometimes greater than in either; while the ductility is usually less, and the density sometimes greater, sometimes less. The colour is not always dependent upon the colours of the constituent metals, as is shown by the brilliant white of speculum metal, which contains 67 per cent. of copper.'

BRONZES.

141. Bronzes are alloys of copper and tin. With a moderate amount of tin the alloy is tough and strong. With more than 20 per cent. of tin it becomes weak and brittle. Up to $17\frac{1}{2}$ per cent. of tin the elastic limit, according to Thurston, lies between 0·5 and 0·6 of the breaking strength. With 25 per cent. it rises up to the breaking weight. With more than 40 per cent. it falls again till it reaches about 0·3 of the breaking strength in pure tin.

Gun-metal for bearings may contain 88 to 95 per cent. of copper. Gun-metal for guns contains usually

[1] *Report of the United States Testing Board*, vol. i., 1878. Also *Materials of Engineering*, Thurston, Part III.

90 per cent. Bell-metal contains 72 to 82 per cent., and speculum metal 67 to 75 per cent. The following table gives values of the tenacity with different proportions of tin :—

Composition		Description	Tenacity, tons per sq in	Authority
Copper	Tin			
92 0	8 0	Gun metal	12 95	Anderson
91·7	8 3	,,	13 84	,,
91 0	9 0	,,	14 73	,,
90 0	10 0	,,	16 96	,,
84 3	15·7	Bell-metal	16 1	Mallet
82 8	17 2	,,	15 2	,,
81·1	18 9	,,	17 7	,,
79 0	21 0	,,	13 6	,,
76 3	23 7	,,	9 7	,,
73 0	27 0	,,	4 9	,,

The following table gives a reduction of those of Thurston's results which relate to the more useful bronzes :—

Composition[1]		Density	Coefficient of bending strength, tons per sq in	Coefficient of elasticity, tons per sq in	Tenacity, tons per sq in	Elongation in 5 inches per cent
Copper	Tin					
96 27	3 73	8 65	14 83	6,132	14 29	14 29
92·8	7 2	8 69	19 52	6,368	12 74	5 53
92 5	7 5	8 68	17 26	6,063	12 46	7 43
90 0	10 0	8 67	22 05	6,255	11 99	3 66
87 5	12 5	8 65	26 96	5,568	13 88	3 56
86·57	13 43	8 68	—	—	13 14	3 33
82 5	17 5	8 79	30 32	6,762	16 16	0 71
80 0	20 0	8 74	25 32	5,938	14 72	0 40

The bars for bending were 1 inch square and 22 inches between supports. The test bars for tension were about $\frac{3}{4}$ inch in diameter.

[1] From original mixing, not analysis

BRASSES.

145. Brass is an alloy of copper and zinc, sometimes with a little lead added. Ordinary brass contains from 66 per cent. copper and 34 per cent. zinc, to 70 per cent. copper and 30 per cent. zinc. Muntz metal, which can be rolled hot, contains 60 per cent. copper and 40 per cent. zinc, or sometimes 66 per cent. copper, 33 per cent. zinc, and 1 per cent. lead.

Mallet obtained the following values for the tenacity of brass :—

Copper	Zinc	Tenacity, in tons per sq. in.
90 7	9 3	12 05
87 7	12 3	13 37
85 4	14·6	14·28
83 0	17 0	13·83
50 0	50 0	8·93

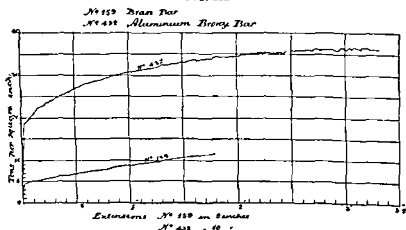
The author obtained for ordinary brass used for machinery a tenacity of 10·43 to 11·62 tons per sq. in., an extension of 13 to 22 per cent. in 8 inches, an contraction of area of 16 to 27 per cent. The
'ent of elasticity bout 5,080 for rolled brass.
table on next gives a selection of Thur-
esults for brass e test bars were similar to
the bronzes escribed.
reat change in racter of the alloy when
exceeds 45 is best marked in the
ults. The c of strength is
from the lo e bar $3\frac{1}{2}$
hich broke

Composition		Density	Coefficient of bending strength, tons per sq. in.	Coefficient of elasticity, tons per sq in	Tenacity, tons per sq. in.	Elongation in 5 inches per cent.
Copper	Tin					
82 5	17·5	8 63	10 35	6,440	14 55	26·7
80	20	8 60	9 46	5,567	14·59	31·4
75	25	8 53	9·97	5,985	13 62	35·8
70	30	8 44	10 92	6,265	13 62	29 2
65	35	8 37	12·70	6,175	16 88	37·7
60	40	8 41	17 40	5,461	18 33	20·7
55	45	8 28	18 95	4,258	19 77	15·3
50	50	8·29	14 91	5,167	13 84	5 0
45	55	—	21 63	6,261	10 78	0 8

Fig. 122 gives an autographic diagram for brass.

146. *Ternary Alloys of Copper, Zinc, and Tin.*—Thurston has made experiments on ternary alloys, with

FIG. 122



a view to determining the strongest of the bronzes. But these results are less completely given, and the tenacities for most appear to be estimated from torsional experiments. Thurston terms the bronzes of composition lying between copper 58 to 54, zinc 44 to 40, and

Alloy	Tenacity, tons per sq in	Elastic limit, tons per sq in.	Elongation in 6 ins, per cent.
10 p c. aluminium bronze	40 8	—	1 5
10 ,, ,,	41·3	26 7	2 5
10 ,, ,,	43 0	38 0	1 0
9 ,, ,,	34 4	23·1	9 0
9 ,, ,,	32 0	19 6	9 0
8½ ,, ,,	32·1	—	28 5
7½ ,, ,,	27·1	20 3	6 0
9 ,, ,,	32 0	—	8·25 [1]
8 ,, ,,	25·8	—	12·5 [1]

A bar of aluminium bronze of a more ductile character was sent to the author by the London branch of the Cowles Company. This bar, about ½ inch in diameter, gave the following results:—

Tenacity	36 78 tons per sq. in.
Elongation in 10 inches .	33 26 per cent.
Contraction	39·87 ,,
Elastic limit	17·74 tons per sq in.

In Fig. 122 the autographic diagram for this bar is given, showing the great toughness of the material.

147. *Effect of Temperature on the Strength of the Alloys.*— Old experiments by a Committee of the Franklin Institute show that the tenacity of copper diminishes with increase of temperature. The following are some of the results:—

Temperature. Fahr.	Tenacity, tons per sq in.	Temperature. Fahr.	Tenacity, tons per sq in.
122	14 73	801	8 48
302	13 84	1016	4 95
545	11 16	2032	0 0

[1] These two tests were made at Watertown, and the elongations were measured in 4 inches

In 1877 experiments were made, under the direction of the Admiralty, at Portsmouth Dockyard, on the effect of temperature on bronzes. The test bars were heated in an oil bath, and then quickly removed to the testing machine and broken, the operation lasting only about a minute. This is not quite so satisfactory as breaking specimens in an oil bath. All varieties of gun-metal in these experiments show a slow decrease of tenacity up to a certain temperature, at which the tenacity suddenly falls to about half its previous value and the ductility is almost lost. The temperature at which the change occurred was about 370° in series I. and 250° in series II. Phosphor-bronze was less affected. Rolled Muntz metal and copper did not suffer serious loss of strength below 500°.

148. *Influence of Mechanical Action on the Strength of Bronze.*[1]—The specimens of bronze were 3 inches in length and 0·077 sq. in. section. They were subjected to the following preparation :—

I. Metal as cast.

II. Metal subjected to a continued tensile stress of 49 cwts., which produced an elongation of 16·7 per cent.

III. Metal subjected to a compressive stress of 15·87 tons per sq. in. for ten minutes before testing.

IV. Metal elongated 20 per cent. by rolling.

Experiment II. shows, in Major-General Uchatius's opinion, that homogeneous bronze is susceptible of

[1] Uchatius. *Proc. Inst. of Civil Engineers*, vol. xlix. 284

Diameter, in inches	Elongation, per cent	Tenacity, in tons per sq in.
Silicium bronze		
080	{1 5 1 0 / 2 0 2 0}	27 61
039	nil	29 37
044	nil	47 41
·036	nil	50 07
081	{1 5 1 0	29 02
	1 5 1 0	27 47
Copper		
081	nil	30 32
082	1 5 2 5	29 16
0847	0 5 1 0	30 31
·081	0 5	28 42

M. Albert Bonnaud gives the following results of tests of three qualities of wire:—I. Iron wire; II. Martin steel wire; III. Crucible steel wire. The tensile tests were made on pieces 14 W.G. (·087 inch diameter) and 16 inches long:—

—	Bigny charcoal iron wire	Firminy wire		
		No I Iron	No II Martin steel	No III Crucible steel
Mean tenacity, tons per sq in	46	57	86	102
Elongation, per cent	0 30	0 37	0 91	0 75
Bendings at right angles before breaking	18	19	20	28

The bendings were over the jaw of a vice of 0·4 inch radius. Lest the high strength here shown should be attributed merely to hard drawing, tests were made on four pieces in each of the following conditions:—(*a*) Rod from rolling mill ready for drawing; (*b*) unfinished wire, drawn down as far as it could be before annealing,

and then annealed in the case of iron and specially tempered in the case of steel; (c) finished wire, drawn down to ·087 inch diameter; (d) finished wire, annealed.

Samples about 22 inches long, ·087 inch diameter		Finished wire No. I. Iron	Finished wire No. II. Steel
Tenacity, in tons per sq. in.	a	27·0	63·4
" "	b	33·3	88·6
" "	c	29·3	101·6
"	d	31·1	54·9
Elongation, per cent	a	7·5 to 16·8	6·2 to 7·0
"	b	22·0	3·0 to 5·7
"	c	0·31 to 0·74	1·2 to 1·8
"	d	20·6	6·8 to 8·0
Bendings at right angles	a	8 to 11	2 to 4
" "	b	20 to 22	4 to 10
" "	c	21 to 29	16 to 37
	d	31	12 to 13

The iron wire retains an increased strength, due to drawing down, even after annealing. The steel wire, on the contrary, is weaker after annealing than the original bar. To utilise the value of the steel fully it must be tempered in such a way that a sufficient flexibility is retained.

Mr. D. K. Clark gives the following values for phosphor-bronze wire[1]:—

—	Unannealed. About 0·6 in. diameter. Tenacity, in tons per sq. in.	Annealed. About 0·11 inch diameter. in t	Extension, per cent.
Lowest	43·6		33
Highest	71·2		
Mean	56·3		

[1] Rul Tables, p

The following table gives a few miscellaneous tests of the strength of wire made by the author :—

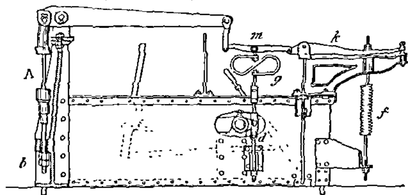
No. of specimen	Description	Diameter	Sq. in. area	Tenacity, tons per sq. in.	Extension in 8 ins., per cent.
—	Brass wire	·1929	·0290	25·23	25·5
112	Black cast steel rod	·191	·0286	62·04	4·12
113	" "	·191	·0286	62·44	5·76
124	Gilding-metal (no tin)	·249	·0487	20·17	6·25
125	" "	·249	·0487	20·62	8·7
127	Soft German silver	·267	·0560	29·89	47·0
128	" "	·267	·0560	29·10	47·7
109	Black shear-steel rod	·194	·0296	50·90	7·0
110	" "	·192	·0289	52·52	6·25
103	Black soft-steel wire	·196	0·302	39·17	11·25
102	" "	·196	0·302	38·07	15·6
106	Bright hard-steel rod	·197	0·305	51·96	7·5
107	" "	·198	0·308	51·45	6·5

Steel pianoforte wire has been produced with a tenacity of 150 tons per sq. inch.

lever g or g' against the spring. By adjusting the springs, the exact stress at which the levers g or g' lift can be arranged. If the test bar is to be twisted in one direction, only one of the levers g or g' is required. If the stroke of the lever h' is large enough it twists the bar alternately in opposite directions, and then both levers, g and g', are used to limit the stresses. When working in adjustment, the stroke of h' is sufficient to just lift one or both the levers g or g' at each stroke.

Wohler's Machine for Repeated Tensions (Fig. 124). —This consists of a wrought-iron bed-plate, at the left-

FIG 124.



hand end of which is a cast-iron standard, supporting the knife-edge of the principal lever h. The test bar A is held in a shackle attached to the lever; the other shackle is attached to an adjusting-screw b. The long arm of the lever is connected by a link to the equal-armed beam m. The centre of this beam is pulled down by a lever worked by a connecting-rod, a bent spring g being interposed to prevent shock. The other end of m rests

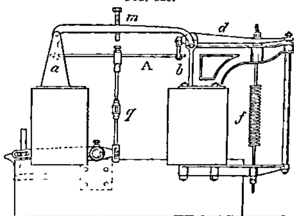
on the short arm of the lever k, which has a bearing-screw and long spring f, as in the torsion machine. If the pull on m exceeds a certain value the lever k lifts, and by adjusting the spring f the tension can be regulated as desired. To facilitate the adjustment the rod d, by which the pull is applied to the beam m, is in two parts, connected by a long coupling nut with right and left hand screws. The rod d is continued down through a bracket, and a nut under this bracket serves to limit the extent to which the test bar is relieved of stress.

In adjusting the machine to give a range of tension between a fixed lower and fixed upper limit, the spring f is first adjusted to the minimum stress. The nut on the end of d can then be adjusted, so that when d rises it just keeps the lever k lifted. Then the spring f is adjusted for the maximum stress, and the machine is ready for use. As made by Wöhler the machine had four sets of levers, so that four bars could be tested simultaneously.

Wöhler's Machine for Repetition of Bending Stresses.—For applying repeated bending stresses to bars, the stress ranging between a fixed lower and upper limit, Wöhler employed the machine shown in Fig. 125. The test bar A rests on knife-edges carried by pairs of links. At a the links are suspended from a fixed bracket. At b they hang from the short arm of the lever d. This lever has a bearing-screw at its longer end, and it is held down by a spring f. The bar is bent by the rod q, furnished with an adjusting coupling, and moved up

and down by a lever and connecting-rod. When the bar is not to be entirely released from stress, but to be strained between a fixed upper and lower limit of stress, the screw *m* is used. As the bar unbends it comes in contact with *m* at some fixed amount of deflection. To adjust the screw *m*, the spring *f* is set to the desired minimum tension, and the screw *m* is then

FIG. 125.

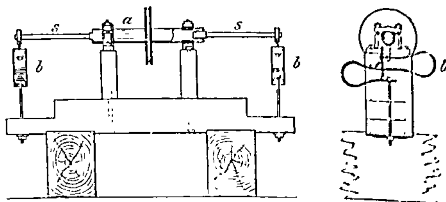


adjusted till it just lifts the lever *d*. Then the spring *f* is set to the maximum tension, and the machine is ready for use.

Wöhler's Machine for Repeated Bending in Opposite Directions.—For repeated bendings in opposite directions Wöhler used the very simple machine shown in Fig. 126. It consists of a wooden frame carrying in bearings the axle *a*, which is rotated by a belt. In the ends of *a* are conical recesses, into which can be fixed by driving two test bars. After being fixed, the test bars are turned in the lathe so as to run truly. At the ends

of the test bars are fixed spring balances, which can be adjusted to any required stress. As the bar rotates

Fig 126



every fibre is subjected to bending alternately in opposite directions, precisely as is the case with journals of railway axles.

152. *Results of Wohler's Endurance Tests.*—The following tables contain all Wohler's more important results. Table I. gives some ordinary statical tests of the materials used in the subsequent endurance tests. The elongation was probably measured in 8 inches, but the length is not given.

Table III. gives Wöhler's results on the endurance of bars subjected to repetitions of tensile stress, the stress in some cases varying from zero to a maximum limit, in others from a minimum to a maximum value. Two forms of bars were tried. The bars marked A had well-rounded corners at the point where the small middle part joined the enlarged end. Those marked B had square corners. It may be noted at once that for any given stress the bars B broke with far fewer repetitions of stress than the bars A. Thus, bar 5 of form A stood 480,000 repetitions of a stress of 17·19 tons per sq. in., while bar 9 of form B stood only 37,000 repetitions of a stress of 17·10 tons per sq. in. Bar 16 of form A was not broken with 13,000,000 repetitions of a stress of 22 tons per sq. in., while bar 21 of form B broke with 35,000 repetitions of this stress.

The next most important point in Table III. is that *the amount of variation of stress*, not the absolute amount of the stress, determines the number of repetitions before fracture. Thus, bars 7 and 8 endured nearly as many repetitions as bar 6, though in the former case the maximum stress was 21 tons and in the latter 15. But then the load was not entirely taken off bars 7 and 8, and the range of stress was only $9\frac{1}{2}$ and $11\frac{1}{2}$ tons. Again, bar 18 is not broken with 12,000,000 repetitions of a stress of 38 tons per sq. in., the minimum load being 19 tons per sq. in.; but bar 10 broke with 19,000 repetitions of a stress of 38 tons, the minimum stress being zero.

TABLE III. WÖHLER'S EXPERIMENTS ON BARS SUBJECTED TO REPEATED TENSIONS BETWEEN DEFINITE LIMITS

No. of bar	Form of bar	Material	Stress applied, in tons per sq. in. Maximum	Minimum	Range of stress, in tons per sq. in.	Number of repetitions before fracture
1	A	Iron axle, Phœnix Company	22·92	0	22·92	800
2	A		21·01	0	21·01	106,910
3	A		19·10	0	19·10	340,853
4	A		17·19	0	17·19	409,481
5	A		17·19	0	17·19	480,852
6	A		15·28	0	15·28	10,141,645
7	A		+ 21·01	+ 9·55	11·46	2,373,424
8	A		+ 21·01	+ 11·46	9·55	[4,000,000][1]
9	B		17·10	0	17·10	37,828
10	A	Krupp's axle steel	38·20	0	38·20	18,741
11	A		33·40	0	33·40	46,286
12	A		28·65	0	28·65	170,170
13	A		26·14	0	26·14	123,770
14	A		23·87	0	23·87	473,766
15	A		22·92	0	22·92	[13,600,000][1]
16	A		21·95	0	21·95	[13,200,000][1]
17	A		+ 38·20	+ 23·87	14·33	[1,801,000][1]
18	A		38·20	19·10	19·10	[12,100,000][1]
19	A		38·20	16·70	21·50	[12,000,000][1]
20	B	Krupp's axle steel	23·89	0	23·89	23,546
21	B		21·97	0	21·97	35,486
22	B		20·08	0	20·08	65,658
23	B		19·10	0	19·10	75,343
24	B		17·18	0	17·18	208,883
25	B		15·29	0	15·29	274,970
26	B		14·34	0	14·34	[1,100,000][1]
27	A	Cast iron from locomotive cylinder	7·62	0	7·62	3,140
28	A		6·69	0	6·69	4,000
29	A		6·22	0	6·22	10,342
30	A		5·73	0	5·73	45,028
31	A		5·26	0	5·26	78,682
32	A		5·03	0	5·03	27,885
33	A		5·03	0	5·03	35,609
34	A		4·78	0	4·78	208,439
35	A		4·78	0	4·78	[7,200,000][1]
36	A		4·78	0	4·78	[7,600,000][1]

[1] Not broken

TABLE IV.—*continued.*

No. of bar	Bars marked H were hardened	Material	Stresses applied, in tons per sq. in. Maximum	Minimum	Range of stress, in tons per sq. in.	No. of repetitions of load before fracture
38	—	Krupp's spring steel	47·75	0	47 75	39,950
39	—		42 95	0	42 95	72,450
40	—		38 20	0	38 20	132,650
41	—		38·20	0	38 20	117,000
42	—		33 40	0	33 40	197,400
43	—		28 65	0	28 65	468,200
44	—		23 87	0	23 87	[40,600,000] [1]
45	—		21 50	0	21·50	[32,942,000] [1]
46	H	Krupp's spring steel	57 30	14·33	42·97	22,900
47	H		,,	19 10	38 20	35,600
48	H		,,	23 87	33·43	86,000
49	H		,,	28 65	28·65	191,100
50	H		,,	33 42	23 88	50,100
51	H		,,	33·42	23 88	251,400
52	H		,,	38 20	19·10	[35,600,000] [1]
53	H		,,	42 95	14 35	33,478,700
54	—	Krupp's spring steel	47 75	7·92	39 83	62,000
55	—		,,	15 92	31 83	149,800
56	—		,,	23 87	23 88	400,050
57	—		,,	27·83	19 92	376,700
58	—		,,	31 52	16·23	[19,673,300] [1]
59	—		42 95	9 55	33 40	81,200
60	—		,,	14 33	28 62	156,200
61	—		,,	19·10	23 85	225,300
62	—		,,	23·87	19 08	1,238,900
63	—		,,	23 87	19 08	300,900
64	—		,,	28·65	14 30	[33,600,000] [1]
65	—		38 20	4·77	33 43	99,700
66	—		,,	9 55	28 65	176,300
67	—		,,	14·33	23 87	619,600
68	—		,,	14·33	23 87	2,135,670
69	—		,,	19·10	19 10	[35,800,000] [1]
70	—		,,	19·10	19 10	[38,000,000] [1]
71	—		,,	26·75	11·45	[36,000,000] [1]
72	—		33 41	4·77	28 64	286,100
73	—		,,	9 55	23 86	701,800
74	—		,,	11 94	21·47	[36,600,000] [1]
75	—		,,	14 33	19·08	[31,150,000] [1]
76	H	Bochum Company's spring steel	52 50	0	52 50	45,850
77	H		47·75	0	47·75	108,850
78	H		42·95	0	42 95	93,800
79	H		38·20	0	38·20	148,400

[1] Not broken

TABLE IV.—*continued*.

No. of bar	Bars marked H were hardened	Material	Stresses applied, in tons per sq in		Range of stress, in tons per sq in	No. of repetitions of load before fracture
			Maximum	Minimum		
80	H	Mayr's spring steel	47·75	0	47 75	39,860
81	—		33 42	0	33 42	212,700
82	—		31 04	0	31 04	360,100
83	—		28 65	0	28 65	[30,500,000][1]
84	—		23 87	0	23 87	[26,260,000][1]
85	H	Seebohm's spring steel	62 10	0	62 10	28,350
86	H		57 30	0	57 30	45,500
87	H		52 50	0	52 50	46,550
88	H		47·75	0	47 75	141,750
89	H		45 35	0	45 35	190,050
90	—	Seebohm's spring steel	42 95	0	42 95	80,850
91	—		38 30	0	38 30	154,000
92	—		33 42	0	33 42	210,000
93	—		28 65	0	28 65	471,800
94	—		26 25	0	26 25	538,850
95	—		23 87	0	23 87	1,165,500

Lastly, Table V. gives the results of experiments on rotating bars subjected to bending As the bar turns round while bent in a fixed direction by the spring, every fibre is alternately in compression and tension, and these are the only experiments of Wohler in which alternate opposite stresses of tension and compression were obtained. The torsional experiments agree with the bending experiments as to the effect of stresses in opposite directions.

Wohler tried three forms of bars in this research. Two of these had square corners at the enlarged end. These two forms were relatively much weaker than the bars of the third form with rounded corners, and only

[1] Not broken

the results of these latter are given in the following table :—

TABLE V WOHLER'S EXPERIMENTS ON BARS SUBJECTED TO REPETITIONS OF TRANSVERSE STRESS (ROTATING BARS) BETWEEN EQUAL AND OPPOSITE LIMITS OF STRESS

No of bar	Material	Stress applied, in tons per sq in		Range of stress, in tons per sq in.	No of repetitions before fracture
		Maximum	Minimum		
1	Iron for axles, Phœnix Company	+15·3	−15 3	30 6	56,430
2		14 3	14 3	28 6	99,000
3		13 4	13 4	26 8	183,145
4		12 4	12 4	24 8	479,490
5		11 5	11 5	23 0	909,840
6		10 5	10 5	21 0	3,632,588
7		9 6	9 6	19 2	4,917,992
8		8 6	8 6	17 2	19,186,791
9		7 6	7 6	15 2	[132,250,000][1]
21	Homogeneous iron	+23 9	−23 9	47 8	2,375
25		22 9	22 9	45 8	4,986
26		21 9	21 9	43 8	11,636
27		18 2	18 2	36 4	31,586
28		16 3	16 3	32 6	94,311
29		14 3	14 3	28 6	161,262
30		13 4	13 4	26 8	464,786
31		12 4	12 4	24 8	636,500
32		11 5	11 5	23 0	3,930,150
33	Krupp's cast-steel axles	+20·1	−20 1	40 2	55,100
34		17 2	17·2	34·4	127,775
35		16·3	16·3	32 6	797,525
36		15 3	15 3	30 6	642,675
37		15·3	15 3	30 6	1,665,580
38		15 3	15 3	30 6	3,114,160
39		14 3	14 3	28 6	4,163,375
40		14 3	14 3	28 6	45,050,640
46	Cast-steel axles, Bochum & Co	+17·2	−17·2	34 4	127,775
47		16 3	16 3	32 6	342,850
48		15 3	15 3	30 6	627,000
49		15·3	15 3	30 6	20,467,780
50		14·3	14 3	28 6	2,845,250
51		14·3	14 3	28 6	[57,360,000][1]
52		13 4	13 4	26 8	3,558,700
53		12 4	12 4	24 8	[11,176,171][1]

[1] Not broken.

TABLE V.—*continued.*

No. of bar	Material	Stress applied in tons per sq. in.		Range of stress, in tons per sq. in.	No. of repetitions before fracture
		Maximum	Minimum		
54	Borsig's cast steel axles	+18·2	−18·2	36·4	157,700
55		17·2	17·2	34·4	257,475
56		16·3	16·3	32·6	533,850
57		15·3	15·3	30·6	1,373,225
58		14·3	14·3	28·6	1,023,625
63	Vickers & Sons' cast steel axles	+16·3	−16·3	32·6	61,240
64		15·3	15·3	30·6	72,940
65		14·3	14·3	28·6	295,800
66		13·4	13·4	26·8	278,740
67		12·4	12·4	24·8	664,900
68		11·5	11·5	23·0	3,275,800
69		10·5	10·5	21·0	[8,000,000][1]
70	Firth & Sons' tool steel	+17·2	−17·2	34·4	370,675
71		16·3	16·3	32·6	691,450
72		15·3	15·3	30·6	253,700
73		14·3	14·3	28·6	1,528,550
74	Copper	+7·64	−7·64	15·28	30,875
75	"	7·64	7·64	15·28	67,725
76	"	6·69	6·69	13·38	480,700
77	"	6·21	6·21	12·42	663,100
78	"	5·97	5·97	11·94	708,000
79	"	5·73	5·73	11·46	2,834,325
80	"	4·78	4·78	9·56	19,327,460

153. *Wohler's Conclusions.*—In certain structures the whole load is a permanent, or dead, load. With such cases Wohler's investigation is not concerned. But in most cases a part or the whole of the load is occasional, or varying. In those cases the engineer has to allow for a practically unlimited number of repetitions of load. Railway axles, for instance, may make 300 million revolutions, involving reversal of stress, before being put out of service. Now, with such varying conditions

[1] Not broken.

of straining action, safety depends, according to Wöhler, not at all on the maximum stress, but only on the range of variation of stress.

The following table gives the stresses and ranges of stress which Wöhler considers to be the limiting values which, in the materials he experimented on, would only produce fracture after an indefinitely large number of repetitions :—

TABLE VI LIMITS OF STRESS FOR UNLIMITED REPETITION OF LOAD (WÖHLER)

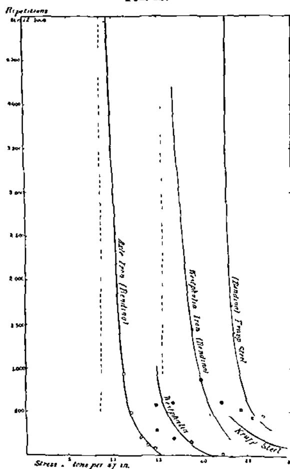
Material	Maximum stress, tons per sq. in.	Minimum stress, tons per sq. in.	Range of stress
A Bars subjected to simple tension, compression, or bending			
Wrought iron	+ 7·65	− 7·65	15·30
" "	+ 15·80	0	15·80
" "	+ 21·00	+ 11·50	9·50
Cast steel axles	+ 13·38	− 13·38	26·76
" "	+ 23·00	0	23·00
" "	+ 38·20	+ 16·70	21·50
Untempered cast-steel springs	+ 23·90	0	23·90
" " "	+ 33·50	+ 11·50	22·00
" " "	+ 38·30	+ 19·10	19·20
" " "	+ 43·00	+ 28·70	14·30
B. Bars subjected to shearing or torsion			
Cast-steel axles .	10·50	− 10·50	21·00
" "	18·20	0	18·20

154. *Experiments by Spangenberg* with Wöhler's machines entirely support Wöhler's conclusions. If the stresses are plotted as abscissæ, and the number of repetitions causing fracture as ordinates, curves are obtained such as those in Fig. 127. These curves cut the axis of abscissæ at the statical breaking stress, and they are asymptotic to a vertical, the abscissa of which

is the stress which the bar will carry if repeated an unlimited number of times.

155. *Endurance Tests made by Mr. B. Baker.*[1]—Mr. B. Baker has given the results of a series of experiments

FIG. 127



on iron and steel made with a machine like that shown in Fig. 126. The rotating bars were 1 inch in diameter

[1] 'Notes on the Working Stress of Iron and Steel' *Am Soc. of Mech. Engineers.* 1886

of straining action, safety depends, according to Wöhler, not at all on the maximum stress, but only on the range of variation of stress.

The following table gives the stresses and ranges of stress which Wohler considers to be the limiting values which, in the materials he experimented on, would only produce fracture after an indefinitely large number of repetitions :—

TABLE VI LIMITS OF STRESS FOR UNLIMITED REPETITION OF LOAD (WOHLER)

Material	Maximum stress, tons per sq in	Minimum stress, tons per sq in	Range of stress
A. Bars subjected to simple tension, compression, or bending			
Wrought iron	+ 7 65	− 7 65	15 30
,, ,,	+ 15 80	0	15 80
,, ,,	+ 21 00	+ 11 50	9 50
Cast-steel axles	+ 13 38	− 13 38	26 76
,, ,,	+ 23 00	0	23 00
,, ,,	+ 38 20	+ 16 70	21 50
Untempered cast-steel springs	+ 23 00	0	23 00
,, ,, ,,	+ 33 50	+ 11 50	22 00
,, ,, ,,	+ 38 30	+ 19 10	19·20
,, ,, ,,	+ 43 00	+ 28 70	14 30
B. Bars subjected to shearing or torsion			
Cast-steel axles	10 50	− 10 50	21 00
,, ,,	18·20	0	18·20

151. *Experiments by Spangenberg* with Wöhler's machines entirely support Wohler's conclusions. If the stresses are plotted as abscissæ, and the number of repetitions causing fracture as ordinates, curves are obtained such as those in Fig. 127. These curves cut the axis of abscissæ at the statical breaking stress, and they are asymptotic to a vertical, the abscissa of which

The following table gives results of experiments on flat bars, some bent alternately in opposite directions, the others bent one way only. The soft steel had a tensile strength of 31·3 tons per sq. in., and an elongation of 20 per cent. in 8 inches. The iron was best bar iron. The bars were 32 inches long, 1 inch wide, and $\frac{1}{2}$ inch thick.

TABLE VIII. ENDURANCE TESTS BARS SUBJECTED TO BENDING (B BAKER)

No.	Material	Stress applied in tons per sq in.		Range of stress, in tons per sq in.	Number of repetitions before fracture
		Maximum	Minimum		
24	Soft steel	+19·7	−19 7	39 4	12,240
25	,,	19·7	19 7	39 4	12,325
26	,,	19 7	19 7	39 4	12,410
27	,,	18 8	18 8	37 6	18,100
28	,,	18 8	18 8	37 6	18,140
29	,,	16 1	16 1	32 2	72,420
30	,,	15 4	15 4	30 8	147,390
31	,,	15 2	15 2	30 4	262,680
32	,,	12 3	12 3	24 6	1,183,200
33	,,	15 4	0	15 4	[3,145,020]
34	Best bar iron	+15 2	−15 2	30 4	184,875
35		15 2	15 2	30 4	250,513
36		15 2	0	15 2	[3,145,020]

The bars 33 and 36 were not actually broken, but when taken out of the machine were found to have deep flaws.

156. *Bauschinger's Experiments on Repeated Tensions.* —Table IX. contains a summary of all Bauschinger's experiments on the endurance of a bar subject to repeated stresses. He constructed a machine of the same kind as Wöhler's, in which a bar could be subjected to stresses ranging from 0 to an upper fixed limit in

tension. He ascertained both the initial elastic limit and the elastic limit acquired under repeated repetition of stress; the initial breaking strength and the strength after the bar had been broken in the Wöhler machine.

TABLE IX. ENDURANCE TESTS BARS SUBJECTED TO TENSION (BAUSCHINGER)

Stresses in tension varying from 0 to an upper limit.)

Material	Elastic limit, in tons per sq. in		Endurance test		Tensile strength, in tons per sq in.	
	Original	Acquired during repetition of loads	Load applied, tons per sq in	No. of repetitions before fracture, in millions	Original	After breaking by repetition of loads
Wrought-iron plate	6·84	12·3	7·1	5·17	25·2	23·6
	6·84	13·2	9·85	5·19	25·2	24·3
	6·84	14·4	13·1	5·18	25·2	24·5
	6·84	16·4	16·4	2·28	25·2	—
Mild-steel plate	15·6	19·4	16·0	6·68	28·5	—
	15·6	18·0	16·0	3·55	28·5	—
	15·6	20·0	16·0	[11·03]	28·5	—[1]
	15·6	16·4	16·0	7·35	28·5	—
	15·6	—	19·7	0·67	28·5	—
	15·6	19·1	19·7	1·01	28·5	—
	15·6	19·0	23·0	0·32	28·5	—
	15·6	19·0	23·0	0·76	28·5	—
	15·6	19·9	23·0	0·16	28·5	—
	15·6	16·4	23·0	0·44	28·5	—
	15·6	15·3	23·0	0·62	28·5	—
	15·6	20·0	26·2	0·34	28·5	—
	15·6	16·9	26·2	0·49	28·5	—
	15·6	17·9	26·2	0·07	28·5	—
	15·6	12·3	26·2	0·11	28·5	—
	15·6	11·5	26·2	0·04	28·5	—
Bar iron	11·8	21·4	13·2	9·11	26·6	28·2
	11·8	10·7	16·4	7·40	26·6	—[2]
	11·8	10·8	19·7	0·64	26·6	—
	11·8	10·6	19·7	0·24	26·6	—
	11·8	10·9	19·7	0·84	26·6	—
	14·8	16·3	13·8	16·48	26·7	27·1
	14·8	18·6	17·2	9·31	26·7	26·6
	14·8	11·9	19·7	0·67	26·7	—

[1] Not yet broken in endurance test

[2] Elastic limit rose to 16·7, and then fell near the end of the endurance test

TABLE IX.—*continued*

Material	Elastic limit, in tons per sq. in.		Endurance test		Tensile strength, in tons per sq. in.	
	Original	Acquired during repetition of loads	Load applied	No. of repetitions before fracture, in millions	Original	After breaking by repetition of loads
Thomas steel axle	17·6	20·4	16·3	[9·58]	40·1	—[1]
	17·6	—	26·2	0·62	40·1	—
	17·6	20·8	19·7	9·01	40·1	41·0
	17·6	—	26·2	0·22	40·1	—
	17·6	—	26·2	0·06	40·1	—
Thomas steel rail	19·0	24·0	16·4	10·19	39·0	39·4
	19·0	17·6	19·7	7·91	39·0	37·7
	19·0	—	26·2	0·57	39·0	—
	19·0	—	26·2	0·56	39·0	
Mild-steel boiler plate	17·6	18·0	18·4	4·85	26·6	—
	17·6	—	21·0	0·40	26·6	—
	17·6	—	21·0	0·49	26·6	—
	17·6	—	21·0	0·88	26·6	—
	17·6	18·4	16·4	6·34	26·6	
	17·6	—	18·7	0·40	26·6	—
	17·6	18·0	16·4	[6·54]	26·6	—[1]
	17·6	16·0	18·7	[4·87]	26·6	—[1]

All the published experiments on endurance have now been brought together and reduced to common measures, because the subject of safe limits of stress, especially in bridges, must before long be reconsidered, and because, while experiments of this kind take a long time to make, it is the number and consistency of the results which are most impressive. A few results of bars breaking with comparatively small stresses might be put aside as possibly accidental or abnormal. But here are four completely independent series of researches, by different observers, with stresses of different kinds, on

[1] Not yet broken

indication of any plastic drawing out, is not uncommon in fractures of tyres, axles, and other structures in ordinary experience.

On what principle, then, is the limit of working-stress in different cases to be decided? As to structures subjected to a purely resting load there is not much practical doubt. There is no evidence that the deformations due to ordinary dead loads on ordinary materials increase with time, however indefinitely prolonged. Secular experiments, such as Sir W. Thomson is making at Glasgow, will probably show that a structure may be loaded with a considerable fraction of its breaking weight and will carry it for a practically unlimited time without sensible increase of deformation. What is exactly the safe limit of stress in this case is not known, but probably there is a limit of stress, such that smaller loads are safe and greater loads unsafe.

157. *Account of the Adoption of Fixed Limits of Working Stress independent of the Conditions of Loading.*—Nothing has hindered so much the recognition of the importance of Wöhler's researches as the existence of officially sanctioned rules for the limits of working stress, and the prevalence of opinions having no better origin than the habit of working to such rules. It will, therefore, not be out of place to indicate how such rules originated. It will appear that they are rather the accidental product of momentary exigencies than the result of any scientific induction. No doubt the ordinary practice of engineers is to divide the statical breaking

strength of a material by an assumed 'factor of safety'[1] to find the proper limit of working stress; and it has, or had, come to be tacitly accepted that the ratio of the working stress to the statical breaking strength measures in all cases the margin of safety.

The so-called factor of safety has been supposed to be required to allow for the following possible causes of weakness:—

1. Variation in the quality of the material.
2. Imperfections of workmanship, causing either scant dimensions or unequal distribution of stress.
3. Corrosion, wear, and other deterioration arising gradually with lapse of time.
4. Errors of calculation, or straining actions neglected.
5. Vibration, shock, and other dynamical actions.

A margin of safety between the working and breaking stresses is undoubtedly required to allow for the contingencies thus enumerated. But it would be impossible, with these contingencies alone in view, to explain the varying factors of safety which are adopted in practice; and, if Wohler's results are true, it is absolutely false to reckon as the margin of security the difference between the calculated working stress and the statical breaking stress.

Previous to 1849[2] no defined rule, recognised

[1] Or, to use an American phrase, 'factor of ignorance'

[2] See a very complete account of the Board of Trade rules, in a paper on the 'Design of Girder Bridges,' by W Shelford and A H Shield. *Brit. Assoc. Report*, 1886

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2. It has long been known that the application of a stress exceeding the elastic limit raised the elastic limit. In certain cases it appeared that the elastic limit could be raised by strain nearly to the breaking stress. This appeared inconsistent with the view that the safe limit of stress could depend on the elastic limit.

A very important memoir by Prof. Bauschinger throws some light on the difficulties thus raised.[1]

Prof. Bauschinger's conclusions rest on extremely delicate measurements of the behaviour of bars in ordinary testing, and are not likely to be generally accepted without further and independent investigation. But this may be said, that the memoirs of Prof. Bauschinger represent an amount of scientific work in testing materials to which there is no parallel in this country, either in the extent and completeness of the researches or the accuracy of the measurements. Prof. Bauschinger believes that his measurements are minute enough to determine definitely the true elastic limit of a material, the limit at which proportionality of the stress and strain first sensibly ceases. Let it be assumed for the moment that such a limit can be definitely ascertained. Then, take this very simple point. It is known that applying a tension to a bar greater than its elastic limit in tension raises its elastic limit in tension. No one has cared to inquire whether such

[1] *Ueber die Veränderung der Elasticitätsgrenze und die Festigkeit des Eisens und Stahls* Mittheilungen aus dem Mech Techn Laboratorium in München 1886

raising of the elastic limit in tension affected the limit in compression. Suppose that initially the elastic limits in tension and compression were 10 tons per sq. in., and that by a load of 15 tons the elastic limit in tension has been raised to 15 tons—it has been universally assumed that the bar would then be perfectly elastic from 10 tons compression to 15 tons tension.[1] But this is exactly what Bauschinger's experiments appear to conclusively disprove. The elastic limit in tension cannot be raised without lowering the limit in compression, and *vice versâ*. Even a moderate raising of the tension limit may lower the compression limit to zero.

This furnishes a complete solution of one of the difficulties in accepting Wohler's laws. When a bar is subjected to alternating compression and extension the elastic limit cannot be raised. Any attempt to raise it in one direction lowers it in the other. The law that the elastic limit can be raised by stress does not apply to a bar subjected to alternate stresses of opposite sign. Why the elastic limit in this case is even lower than the primitive elastic limit in most cases will be discussed presently. At present, it is enough that under alternating stresses we cannot expect that the elastic limit will rise, and therefore *cannot expect a bar to be safe* under a range of stress greater than that between its primitive elastic limits.

[1] One single exception should be noted Prof James Thompson, in 1877, stated that the common assumption that the elastic limit could be extended both for compression and tension was unproved, and that the determination of the point was a matter of importance in the theory of elasticity.—*Encyclopædia Britannica*, "Elasticity."

Next consider the case of a stress of one kind only. Bauschinger's experiments, like earlier experiments, show that under stresses of one kind only, the elastic limit of a bar can be raised by strain nearly to the breaking stress. But they show, at the same time, that these artificially produced elastic limits are extremely unstable. The following table illustrates these points.

TABLE X. BAUSCHINGER'S EXPERIMENTS ON THE CHANGE OF POSITION OF THE ELASTIC LIMIT

(Bar subjected to tension only. Tons per sq. in.)

Treatment	Elastic limit	Yielding stress or breaking-down point	Greatest stress imposed on bar
Bar of Bessemer steel, No. 939a			
1 Original condition	11·6	17·4	22·6
2 One day after	—	24·8	26·8
3 Immediately after (2)	8·05	27·0	28·3
4 Immediately after (3)	—	28·3	29·6
5 One day after (4) Broke with 34 tons	—	32·4	34·0
Bar 939b. Same steel			
1. Original condition	12·0	18·6	21·3
2 69 hours after (1)	20·0	24·0	26·6
3 Half an hour after (2), straightened in the lathe	4·05	25·6	32·3
4 68 hours after (3)	6·9	33·0	33·0
5 3 years after (4)	33·0	33·0	33·0
6 2 days after, and after being vibrated by hammering on end	12·5	32·0	32·0
7 After 2 years, and after heating to cherry red and cooling in water Broke at 35·8 tons	0	24·6	25·2

It will be seen, in the case of the first bar, that loading again immediately after stretching to the yielding point, the elastic limit is lowered from 11·6 to 8·05 tons. In the case of the second bar, similarly strained

but with a period of rest of 69 hours allowed, the elastic limit is raised from 12 to 20 tons. But on reloading immediately the elastic limit is lowered to 4·05 tons. With a three years' period of rest it is raised to 33 tons, just the load with which it had previously been strained. But this artificially produced elastic limit is so unstable that on hammering the bar on the end and reloading it has fallen to 12·5 tons.

Now, to return to the case of a bar subjected to alternate compressions and tensions. It was seen that one of the difficulties of Wöhler's laws was, that the limit of safe stress for alternate tensions and compressions is a stress less than the primitive tensile elastic limit. Bauschinger explains this by advancing the view that the primitive elastic limit of many materials is an artificially raised elastic limit. The material has been subjected to mechanical operations in manufacture which are equivalent to straining actions. Now, Bauschinger found that alternate compression and extension had the effect of raising an artificially lowered, or lowering an artificially raised, elastic limit. By subjecting a bar to a few alternations of equal stresses, which are equal to or somewhat exceed the elastic limits, they tend towards fixed positions which Bauschinger calls the natural elastic limits. The range of stress for which a bar is perfectly elastic after a few repetitions of such alternating stresses appears to agree very closely with Wöhler's range of stress for unlimited repetitions of alternating stresses.

TABLE XI BAUSCHINGER'S EXPERIMENTS ON ALTERNATE TENSION AND COMPRESSION

(Tons per square inch)

Time between the loadings	Elastic limit		[illegible]	
	Tension	Compression	Tension	Compression
Wrought iron bar				
1 Original condition	—	—	13 7	
2 6 days	13 7	—	14 5	
3. 1 hour	—	4 8		
4 5 minutes		9 65		14 5
5 20 hours	—	12 9		14 5
6 1 hour	—	—	14 5	14 5
7 46 minutes	—			
8 30½ hours	—			14 5
9 15½ hours	—	—	6 45	6 45
10. 2 hours	4 8		7 25	
11 9 minutes	—		7 25	
12 27 hours	—	—		
13 30 minutes	—	12 7		17 5
14 3 days.	—	—	17 5	17 5
15 2 days	—	4 8		6 35
16 2 days.	—	—	6 35	
17 5 hours	—	7 15		—
18 Next day	6 35	—	7 15	7 15
19. 2 days	—	—	—	
20 2½ hours	7 15	—	7 95	7 15
21. 4½ hours	—	7 95	—	—
22 1 day	8 75	—	8 75	8 75
23 9 hours	—	7 95	—	9 55
Bessemer steel bar				
1. Original condition	17 7	—	24 0	—
2 23 hours	—	3 24	—	24 3
3 5 hours	1 6	—	24 0	—
4 4 days	—	4 85	—	8 5
5 2 days	5 55	—	8 5	—
6 5½ hours	—	8 85	—	9 7
7 21½ hours	8 85	—	9 7	—
8 2 days	—	—	—	9 7
9 4 hours	10 5	—	11 3	—
10 2¼ hours	—	9 65	—	11 3
11 16 hours	9 65	—	11 3	—
12 23 hours	—	9 65	—	11 3

The preceding table illustrates Bauschinger's attempt to find the natural elastic limits by alternating stresses in tension and compression. It will be seen that after a

succession of loads in tension which lower the limit in compression, and of loads in compression which lower the limit in tension, the elastic limit settles down—as the loads are diminished towards an amount not greatly exceeding the elastic limit—to a value not greatly different in tension and compression, and below the initial elastic limit. Further, the limits thus obtained—about 8 tons for wrought iron and 9½ tons for mild steel—differ very little from the stresses which Wöhler found to be the greatest which a bar would bear indefinitely when subjected to equal alternating stresses.

The tables given are only a sample of the numerous tables in Professor Bauschinger's memoir. But these may serve to show that the elastic limits of a material are variable limits, restricted only by this, that the range of perfect elasticity seems to be a fixed range. In this a point of agreement is found with Wöhler's results.

Elastic Limit in Bauschinger's Endurance Tests.—In the endurance tests given in Table IX. the initial elastic limit, which was determined from measurements on a 5-inch length of bar, and the elastic limit acquired during repetition of stress, are given. It will be seen that the elastic limit usually rises with repetition of stress to a point above the load applied. When that is the case, the bar suffers a large number of repetitions of load before fracture. If the elastic limit is very near to, or below, the load applied, the bar breaks with comparatively few repetitions of load. As far as the statical strength of the bar is concerned, it

does not appear to be diminished by any number of repetitions of load. There is a small diminution in wrought iron, and an increase in other cases.

159. *Gerber's Parabola.*—Suppose the ranges of stress for unlimited repetition known for any material. Then it has been shown that, if the ranges of stress are plotted as ordinates, and the minimum stress as abscissæ, the points fall on a parabolic curve

Let f_{max}, f_{min} be the limits of stress, and $\Delta = f_{max} \mp f_{min}$ be the range of stress. The upper sign is to be taken if the stresses are of the same kind, and the lower if they are of different kinds. Let f be the statical breaking strength. Then Gerber's equation is—

$$(f_{min} + \tfrac{1}{2}\Delta)^2 + k\,\Delta = f^2;$$

where k is a constant for any material. If the statical strength f is known, and the value of f_{min} and f_{max} for any one range of stress at which the bar stands a practically unlimited number of repetitions before breaking, then k can be determined, and the limits of stress for all conditions of loading can be calculated

The values of k have been calculated for all Wöhler's and Bauschinger's experiments in which the bars stood over 5 million repetitions of load, and from the equations the parabolas in Fig. 128 have been drawn. It will be seen that these quite independent experiments give fairly consistent values for the ranges of stress under all conditions of loading. Bauschinger's results are specially valuable in connection with

succession of loads in tension which lower the limit in compression, and of loads in compression which lower the limit in tension, the elastic limit settles down—as the loads are diminished towards an amount not greatly exceeding the elastic limit—to a value not greatly different in tension and compression, and below the initial elastic limit. Further, the limits thus obtained—about 8 tons for wrought iron and $9\frac{1}{2}$ tons for mild steel—differ very little from the stresses which Wöhler found to be the greatest which a bar would bear indefinitely when subjected to equal alternating stresses.

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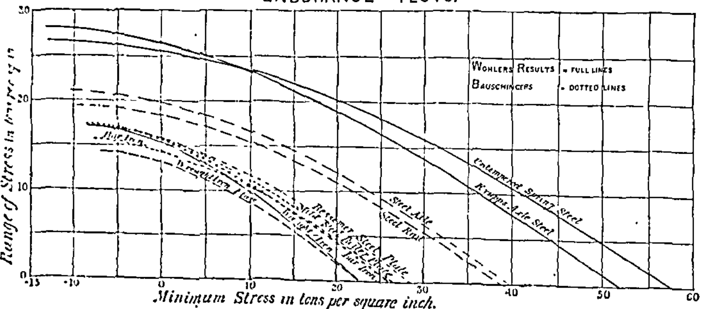
Let f_{max}, f_{min} be the limits of stress, and $\Delta = f_{max} \mp f_{min}$ be the range of stress. The upper sign is to be taken if the stresses are of the same kind, and the lower if they are of different kinds. Let f be the statical breaking strength. Then Gerber's equation is—

$$(f_{min} + \tfrac{1}{2}\Delta)^2 + k\,\Delta = f^2;$$

where k is a constant for any material. If the statical strength f is known, and the value of f_{min} and f_{max} for any one range of stress at which the bar stands a practically unlimited number of repetitions before breaking, then k can be determined, and the limits of stress for all conditions of loading can be calculated.

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FIG 128.


WOHLER'S AND BAUSCHINGER'S
ENDURANCE TESTS.
WOHLERS RESULTS = FULL LINES
BAUSCHINGERS = DOTTED LINES
Untempered Spring Steel
Krupps Axle Steel
Steel Axle
Steel Rail
Bessemer Steel Plate
Wrought Iron
Minimum Stress in tons per square inch.
-15
-10
0
10
20
30
40
50
60
0
10
20
30

Wöhler's, because in two of the materials used by Wöhler the statical strength was exceptionally high.

The following tables give the values of f_{max} and f_{min} for the most useful cases, recalculated from the same equations. The last column is of course the experimentally determined breaking strength of the material used :—

TABLE XII BAUSCHINGER'S ENDURANCE TESTS.

(Stresses requiring 5 to 10 million repetitions to cause fracture. Tons per sq. in.)

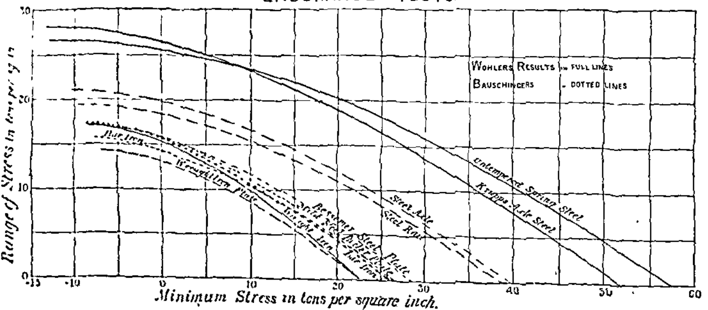
Material	Opposite stresses		One stress zero		Similar stresses		Range zero, Ultimate statical strength
	Least	Greatest	Least	Greatest	Least	Greatest	
Wrought-iron plate .	– 7 15	+ 7 15	0	13 10	11 4	19 2	22 8
Bar iron	– 7 85	+ 7 85	0	14 4	13 3	22 02	26 6
Bar iron .	– 8 65	+ 8 65	0	15 75	13 2	21 92	26 4
Bessemer mild steel plate	– 8 55	+ 8 55	0	15 70	14 3	23 8	28 6
Steel axle	– 10 5	+ 10 5	0	19 70	20 0	32 1	40 0
Steel rail	– 9 7	+ 9 7	0	18 4	19 5	30 85	39 0
Mild-steel boiler plate	– 8 65	+ 8 65	6	15 8	13 3	22 55	26·6

TABLE XIII LIMITS OF STRESS, FROM WÖHLER'S ENDURANCE TESTS

(Stresses, in tons per sq. in., for which fracture occurs only after an indefinitely large number of repetitions.)

Material	Opposite stresses		One stress zero		Similar stresses		Range zero, Ultimate statical strength
	Least	Greatest	Least	Greatest	Least	Greatest	
Wrought iron	– 8 6	+ 8 6	0	15 25	12 0	20 5	22 8
Krupp's axle steel	– 14·05	+ 14 05	0	26 5	17 5	37 75	52 0
Untempered spring steel	– 13 38	+ 13 38	0	25 5	12 5	34 75	57 5

Fig 128


WOHLER'S AND BAUSCHINGER'S
ENDURANCE TESTS.
Wohlers Results in full lines
Bauschingers - dotted lines
Untempered Spring Steel
Krupps Axle Steel
Steel Axle
Steel Rail
Bar Iron
Wrought Iron Plate
Wrought Iron
Bessemer Steel Plate
Range of Stress in tons per sq in
Minimum Stress in tons per square inch.
30
20
10
0
-15
-10
0
10
20
30
40
50
60

PROPERTIES OF TIMBER, FROM SMALL TEST SPECIMENS.

Kind of timber	Length of seasoning, years	Coefficient of elasticity for tension, tons per sq in	Tenacity along fibre, tons per sq. in.	Crushing strength along fibre, tons per sq in.	Coefficient of bending strength, tons per sq in.	Shearing resistance along fibres, tons per sq in
Yellow pine .	—	—	—	2 41	—	—
Spruce . .	—	714	5 54	—	4 91	0 27
Red pine	—	750	5 80	2 59	3 71	0 29
British oak	—	656	6 70	4 46	5 27	1 03
Teak, Indian	—	1,071	6 70	5 36	6 92	—
Mahogany	4	—	5 51	3 30	4 46	—
White oak	1–2	—	8 70	2 81	4 46	—
,, ,, .	13-18	—	8 93	2 88	4 69	—
Spruce .	1	—	5 44	2 66	2 68	—
Yellow pine	1-6	—	6 87	3 60	4 51	—
Lignum vitæ	4	—	7 14	4 40	7 18	—
Pitch pine	3	—	5 09	3 99	—	—
White pine	4	—	5 10	2 24	3 03	—
Ironbark	—	871	7 12	4 54	8 15	—
Blue gum .	—	910	8 97	3 45	5 86	—
Jarrah .	—	317	1 31	3 20	4 13	—

161. *Bauschinger's Investigation of the Elasticity and Strength of Pine Wood.*—By far the most thorough and valuable investigation of the properties of timber is contained in two papers in the 'Mittheilungen,' of the Munich Laboratory.[1] In Bauschinger's earlier investigation the object was to determine the conditions which should be observed in testing timber, the relative value of different modes of testing, the influence of conditions of growth, time of felling, and seasoning on the strength of timber, and the relations between the physical constants of the material. Bauschinger immediately found that the amount of moisture in the timber had a very great influence on

[1] *Mittheilungen aus dem Mech. Tech. Laboratorium in Munchen.* 1883 and 1887.

and decreasing with it. The bending tests on beams of the full useful section of the log showed generally that the strength and coefficient of elasticity varied directly with the density. The results were, however, influenced by the presence of knots and other defects. The pressure tests gave, on the whole, the most uniform results, the section of the test pieces being fairly large, and a uniform distribution of stress being fairly well obtained. But the elastic limit and coefficient of elasticity are difficult to ascertain accurately in pressure tests. The strength increases with the density, but the heart pieces are weak. In timber tested within three months of felling, the winter-felled timber was 25 per cent. stronger than summer felled. But later researches showed that this difference disappeared after a longer time of seasoning. The strength increases in seasoning, but the increase probably ceases after about one year.

Bauschinger concludes that when the question is the average quality of a timber, as in inquiries with reference to the influence of time of felling or seasoning, or the influence of the soil or locality of growth, then the pressure tests are the easiest and most trustworthy. Discs about 6 inches thick should be sawn from each end and the middle of the log, and these then divided into four sectors. From each of these a square prism should be cut, the height being 1½ times the length of side. The compressive strength should then be ascertained for as nearly as possible the standard dryness (15 per cent. of moisture). The test pieces should be measured,

and weighed to determine the density. The coefficient of elasticity is best determined from bending tests of a beam of the whole useful section of the log. As this depends on the quality of the whole section, and is determined for stresses within the elastic limit, it is probably a very valuable indication of the structural value of the timber. By plotting his results, Bauschinger shows that there is a definite relation between the coefficient of elasticity and the bending and crushing strength, and that this can probably be expressed by a linear equation. There is also a definite relation in pine wood between the density and the strength, expressed by the following equation :—

$$\beta = 6{\cdot}35\,\delta - 0{\cdot}635,$$

where β is the crushing strength in tons per sq. in., and δ the density at a standard dryness of 15 per cent.

The following are some of the results in the earlier research, the timber being tested about three months after felling :—

TENSION EXPERIMENTS

(Test pieces, 1·6 × 0·4 inch section. Mean values as tested.)

Timber	Locality	Summer felled Tenacity, tons per sq. in.			Winter felled Tenacity, tons per sq. in.		
		Circumference	Heart	Mean of log	Circumference	Heart	Mean of log
Red pine	Lichtenhoff	6·67	1·46	5·01	4·76	1·84	3·78
Spruce	Frankenhofen	6·10	1·97	4·76	7·87	2·19	5·97
,,	Regenhutte	6·54	2·60	5·24	6·10	1·90	4·70
,,	Schliersee	6·44	1·84	3·59	3·68	1·62	2·99

AVERAGE CRUSHING STRENGTH OF WHOLE SECTION OF LOG

(Ten per cent. moisture. Tons per sq. In.)

Time of felling	Lichtenhoff		Frankenhofen		Regenshütte		Schliersee	
	A	B	A	B	A	B	A	B
Summer felled	2·34	3·21	2·15	2·86	2·37	2·81	1·40	2·04
Winter felled	3·03	2·83	2·51	2·95	2·39	2·83	1·89	2·13

A Tested 3 months after felling
B Tested 5 years after felling

162. *American Tests of Timber, with Large sized Test Pieces.*—It has already been stated that tests of large test pieces give values of the strength of timber considerably smaller than those obtained from small test pieces. Of tests with large test pieces the most important are those made in the United States, chiefly under the direction of Prof. Lanza, of the Massachusetts Institute of Technology.[1]

Prof. Lanza appears to have failed to make satisfactory tension experiments on large specimens. He concludes that tie bars used in construction will always give way in some other manner than by direct tearing for instance, by pulling out the fastenings, and shearing and splitting the timber. Tests of crushing strength are much less difficult. The following table gives a summary of a series of tests of wooden posts, generally 7 to 10 inches in diameter, made for an insurance company under Prof. Lanza's direction. In all these tests

[1] *Applied Mechanics*, Lanza, p. 497. Also, 'Report on Strength of Wooden Columns,' Lanza, and Executive Document 12, Forty-seventh Congress, First Session.

Pressure Experiments.

(Test pieces, about 3½ × 3½ inches, and 6 inches long Mean strength, as tested, and also reduced to a standard dryness—10 per cent. of moisture.)

Timber	Locality	Summer felled. Compressive strength, in tons per sq. in.		Winter felled. Compressive strength, in tons per sq. in.	
		As tested	Standard dryness	As tested	Standard dryness
Red pine	Lichtenhoff	1·78 [19]	2 37	2 03 [26]	3 20
Spruce	Frankenhofen	1 56 [20]	2 13	1 99 [17]	2 50
,,	Regenhutte	1 49 [27]	2 41	1·78 [20]	2 43
,,	Schliersee	1 03 [20]	1 41	1 43 [19]	1·89

The figures in brackets give the moisture per cent

Bending Experiments

(Beams, about 7½ × 7½ inches, and 93 inches span. Mean values. The upper value for each timber is for a summer, and the lower for a winter, felled tree.)

Timber	Locality	Coefficient of elasticity, tons per sq in	Elastic limit, tons per sq. in.	Coefficient of bending strength, tons per sq in.	Density	Content of moisture, per cent.
Red pine	Lichtenhoff	686	1 28	3 00	0 50	23
,,	,,	654	1 40	2 86	0 55	33
Spruce	Frankenhofen	698	1·45	2 66	0 45	29
,,	,,	737	1 66	2 86	0·45	27
,,	Regenhutte	730	1·37	2 64	0 46	34
,,	,,	698	1·44	2 83	0 43	31
,,	Schliersee	464	0·93	1·87	0 355	23 5
,,	,,	438	0 84	1 63	0 375	25

These results are directly comparable with Lanza's results, given below. These latter were also on pretty large beams.

The influence of a longer time of seasoning is shown in the following table :—

AVERAGE CRUSHING STRENGTH OF WHOLE SECTION OF LOG.

(Ten per cent. moisture. Tons per sq in)

Time of felling	Lichtenhoff		Frankenhofen		Regenshutte		Schliersee	
	A	B	A	B	A	B	A	B
Summer felled	2 34	3 21	2 15	2 86	2 37	2 81	1·40	2 04
Winter felled	3 03	2 83	2 51	2 95	2 39	2 83	1 89	2 13

A Tested 3 months after felling
B Tested 5 years after felling

162. *American Tests of Timber, with Large-sized Test Pieces.*—It has already been stated that tests of large test pieces give values of the strength of timber considerably smaller than those obtained from small test pieces. Of tests with large test pieces the most important are those made in the United States, chiefly under the direction of Prof. Lanza, of the Massachusetts Institute of Technology.[1]

Prof. Lanza appears to have failed to make satisfactory tension experiments on large specimens. He concludes that tie bars used in construction will always give way in some other manner than by direct tearing—for instance, by pulling out the fastenings, and shearing and splitting the timber. Tests of crushing strength are much less difficult. The following table gives a summary of a series of tests of wooden posts, generally 7 to 10 inches in diameter, made for an insurance company under Prof. Lanza's direction. In all these tests

[1] *Applied Mechanics.* Lanza, p 497 Also, 'Report on Strength of Wooden Columns,' Lanza, and Executive Document 12, Forty-seventh Congress, First Session

the strength was simply proportional to the area of cross section, the deflection laterally being insignificant.

TESTS OF WOODEN POSTS AND BLOCKS, USUALLY WITH FLAT ENDS (LANZA).

Form	Approximate size		Crushing strength, in tons per sq. in.			Coefficient of elasticity, tons per sq. in.
	Length, feet	Section, sq. ins.	Max.	Min.	Mean	
			YELLOW PINE			
Round	12	30·65	2·10	1·63	1·97	728-984
,,	12	45·61	2·05	1·82	1·94	949
,,	2	48·86	2·10	1·93	2·01	734-1091
Rectang	12	100	—	—	2·33[1]	—
,,	2	81-103	—	—	2·41	—
Round	--	45-48	2·18	1·61	1·90	—
			WHITE OAK			
Round	12	32·63	1·69	1·31	1·56	545-781
,,	2	47-93	1·99	1·40	1·57	493-582
			OLD AND SEASONED WHITE OAK			
Round	12	24	2·69	2·05	2·23	823-955
,,	12	27	1·89	1·31	1·57[2]	—
,,	13	79·87	2·08	1·73	1·92	646-916
,,	11½	60·65	2·18	1·53	1·82	—

Another series of tests on large rectangular posts of white and yellow pine timber was made with the Watertown machine. The lengths varied up to 30 feet. The results are too numerous to give here, but they have been plotted by Mr. E. F. Ely, of the Massachusetts Institute of Technology, and from the plotting the following rule is derived. The posts had flat ends, and the load was evenly distributed.

Let l be the length, and r the least sectional dimension. Then, the crushing stress f per sq. in. of section in tons is as follows :—

[1] One end flat, one with rectang. pintle. [2] Maple cap and oak base.

White pine		Yellow pine	
$\frac{l}{r}$	f	$\frac{l}{r}$	f
0-10	1·116	0-15	1·785
10-35	·893	15-30	1·562
35-45	·669	30-40	1·339
45-60	·446	40-45	1·116
—	—	45-50	·893
—	—	50-60	·669

163. *Bending Tests.*—The American bending tests are not on so large a scale as those on crushing, but, with the exception of those of Bauschinger already given, they afford the most trustworthy data as to the strength of timber beams. They were made under Prof. Lanza's direction. The beams were 2 to 6 inches wide, and 2 to 12 inches deep. The span varied from 4 to 20 feet.

Usually, in bending tests, the beam is supported at the ends and loaded at the centre. Let W be the load at the centre; b and h the breadth and depth of the beam; l the span of the beam; the dimensions being in inches, and the load in tons. Let f be the greatest direct stress on the fibres furthest from the neutral axis; f_s the shearing stress at the neutral axis, in tons per sq. in.; δ the deflection at the centre, in inches. Then, so long as the elastic limit for bending is not exceeded,

$$W = \tfrac{2}{3} f \frac{b h^2}{l}; \quad f = \tfrac{3}{2} \frac{W l}{b h^2} \qquad (1).$$

$$\delta = \tfrac{1}{4} \frac{W l^3}{E b h^3}; \quad E = \tfrac{1}{4} \frac{W l^3}{\delta b h^3} \qquad (2).$$

$$f_s = \tfrac{3}{4} \frac{W}{b h} \qquad (3).$$

Equation (1) may be used to determine the dimensions for a given limit of stress ; and equation (2) to determine the coefficient of elasticity of the timber, from observations within the elastic limit. When, however, W is the load which breaks the beam, the value of f obtained from equation (1) is no longer the real stress in the beam. Since, however, it is a convenient measure of the strength of the timber for practical purposes, it may be called the coefficient of bending strength. The coefficient of bending strength is always greater than the real breaking stress. From the great weakness of timber along the grain, beams give way about as often by shearing along the neutral surface as by tearing the extreme fibres. Then the shearing stress f_s calculated by equation (3), bears a similar relation to the real shearing stress that f bears to the real tenacity of the timber.

The following summary gives the most important results of Professor Lanza's bending tests :—

—		Coefficient of bending strength, tons per sq. in.	Coefficient of elasticity, tons per sq. in.
Spruce beams	Max.	3·910	709
" "	Min	1·337	401
" "	Mean	2·180	594
Yellow pine beams	Max.	5·071	1,063
" " "	Min.	1·769	619
" " "	Mean	3·255	779
Oak beams	Max	3·419	789
" "	Min	2·225	281
" "	Mean	2·712	555
White pine	Max	3·237	572
" "	Min.	1·585	413
" "	Mean	2·116	481

Beams which gave way by Shearing.—In Lanza's tests six spruce beams and five yellow pine beams gave way by longitudinal shearing near the neutral axis. The intensity of the shearing stress varied from 117 to 248 lbs. per sq. in. in the spruce beams, and from 153 to 397 lbs. per sq. in. in the yellow pine beams. The mean values were—

	Shearing strength, lbs per sq in.	tons per sq. in.
Spruce beams	191	. 0 0853
Yellow pine beams	248	. 0 1107

On the beams which did not fail by shearing the mean intensity of shearing stress was about the same. *Hence it may be concluded that, for soft wood timber, beams give way by shearing at the neutral axis or by tearing at the convex surface almost indifferently.*

164. *Direct Experiments on Shearing along the Grain.*—Direct experiments on the shearing resistance along the grain were made at the Watertown Arsenal, and gave somewhat higher values of the shearing strength. This is probably due to the fact that, in shearing experiments, the timber is forced to shear at a selected section, while in the beam experiments the shearing occurred along the weakest of the planes near the neutral axis of the beam. The specimens were also comparatively small.

SHEARING TESTS (WATERTOWN ARSENAL)

	Shearing strength, lbs. per sq in
Ash	458 to 700
Yellow birch	563 ,, 815
White maple	367 ,, 647
Red oak	726 ,, 999
White oak	752 ,, 966
White pine	267 ,, 366
Yellow pine	286 ,, 415
Spruce	253 ,, 374
Whitewood	382 ,, 406

The greater shearing strength of the leaf woods is noticeable.

165. *Influence of Time on Bending Strength and Elasticity.*—Experiments by Herman Haupt, and more recent experiments by Thurston [1] and Kidder,[2] show: (1) That the deflection of a beam of pine under a statical load increases with time, or the modulus of elasticity is less for a prolonged than for an immediate loading; (2) that the beam breaks in course of time with a statical load a good deal less than that required to break it immediately. In Thurston's experiments a plank of yellow pine was selected. Bars $1\frac{1}{4}$ to 3 inches square, and 40 to 54 inches long, gave a density of 0·75 to 1·0, a coefficient of bending strength of 4·91 to 5·36 tons per sq in., and a coefficient of elasticity of 1,005 tons per sq. in. Kiln dried, the coefficient of bending strength increased one-fifth, and that of elasticity one-ninth. For a bar 1 inch square on supports 40 inches apart the centre breaking load was 375 lbs. Nine bars of this size were prepared, three being loaded with 350 lbs., three with 300 lbs., and three with 250 lbs. at the centre. All the first three broke in less than 13 hours; all the second three in from 80 to 719 hours; and all the third set, loaded with only 60 per cent. of the immediate breaking weight, broke in from 6,000 to 11,000 hours. These experiments seem to

[1] *Proc. Am. Assoc. for Advancement of Science*, 1881. *Proc. Inst. C.E.* lxxi. p. 428.

[2] *Journal of Franklin Institute*, 1882. *Proc. Inst. C.E.* lxxi. p. 431.

show that a statical load of 60 per cent. of the immediate breaking weight is not safe. When broken immediately, the ultimate deflection was about 1·8 inch; with 350 lbs. it was 2·3 inches; with 300 lbs. 3·0 inches, and with 250 lbs. 2·5 inches. Hence the deflection is greater with a prolonged load. In Mr. Kidder's experiments on dry spruce beams $1\frac{1}{2}$ inch square, the deflection increased with time, even when as small as $\frac{1}{15}$th of the immediate breaking weight. He concluded that one-half the immediate breaking weight could not be permanently supported.

LEATHER BELTING

The following few results may find place here :—

STRENGTH OF LEATHER BELTS AND FASTENINGS

—	Dimensions, in inches	Tenacity, in lbs per inch of width	Authority
Single leather Max		1,600	Rieble Bros
,, ,, Min	2 0 × 0 2	700	,, ,,
,, ,, Mean		1,280	,, ,,
,, ,, Max		1,272	Unwin
,, ,, Min	2 5 × 206	616	,,
,, ,, Mean		964	,,
Double belt, copper sewn	2 5 × 314	1,110	
Single belt, ordinary laced joint	2 5 × 203	473	,,
,, ,, butt laced	3 0 × 21	265	,,
,, ,, joint scarfed and glued.	3 0 × 21	544	
,, ,, grip fastener	2 5 × 22	242	,,
,, ,, Crowley's fastener	3 0 × 21	635	,,
,, ,, hose riveted, 12, $\frac{3}{14}$ rivets in two rows	7 0 × 22	394	Watertown

The greater shearing strength of the leaf woods is noticeable.

165. *Influence of Time on Bending Strength and Elasticity.*—Experiments by Herman Haupt, and more recent experiments by Thurston [1] and Kidder,[2] show: (1) That the deflection of a beam of pine under a statical load increases with time, or the modulus of elasticity is less for a prolonged than for an immediate loading; (2) that the beam breaks in course of time with a statical load a good deal less than that required to break it immediately. In Thurston's experiments a plank of yellow pine was selected. Bars $1\frac{1}{4}$ to 3 inches square, and 40 to 54 inches long, gave a density of 0·75 to 1·0, a coefficient of bending strength of 4·91 to 5·36 tons per sq. in., and a coefficient of elasticity of 1,005 tons per sq. in. Kiln dried, the coefficient of bending strength increased one-fifth, and that of elasticity one-ninth. For a bar 1 inch square on supports 40 inches apart the centre breaking load was 375 lbs. Nine bars of this size were prepared, three being loaded with 350 lbs., three with 300 lbs., and three with 250 lbs. at the centre. All the first three broke in less than 43 hours; all the second three in from 80 to 719 hours; and all the third set, loaded with only 60 per cent. of the immediate breaking weight, broke in from 6,000 to 11,000 hours. These experiments seem to

[1] *Proc. Am. Assoc. for Advancement of Science*, 1881. *Proc. Inst. C.E.* lxxi. p. 428.

[2] *Journal of Franklin Institute*, 1882. *Proc. Inst. C.E.* lxxi. p. 431.

silica, alumina, oxide of iron, lime, and magnesia. Silica occurs nearly pure as quartz, flint, and sand, and is almost universally present in combination with other earthy bases. Alumina, combined with silica, occurs in clay, and in mica and felspar. Magnesia occurs combined with silica in soapstone, augite, and hornblende, and as a carbonate in some limestones. Lime occurs as a carbonate, nearly pure, in some limestones

The most important building stones may be classed as granite, clayslate, sandstone, or limestone.

Granite consists normally of quartz, colourless and transparent ; felspar, opaque, red, yellow, or grey, giving the prevailing tint to the rock; and mica. Hornblende and talc are sometimes associated with or replace the mica. Granite is an extremely valuable building stone. It is heavy, strong, non-absorbent, and capable of taking a fine polish. On the other hand, it stands fire badly, and is difficult to work. The hornblendic varieties have great resistance to abrasion. Inferior granites sometimes decay, either by decomposition of the felspar, or by surface disintegration by frost.

Trap, Greenstone and Basalt have some of the qualities of granite. They are compact crystalline rocks, composed of felspar, hornblende, and augite. They are strong, but difficult to dress.

Clayslate, composed of quartz and mica, is sometimes a very compact rock, yielding a fine-grained and strong building stone. Sometimes the slaty cleavage is so developed that it yields slabs and roofing slates.

Sandstones are stratified rocks, composed largely of quartz grains, with a siliceous, clayey, or calcareous cement. The fineness of grain varies greatly. In some sandstones the cement is nearly pure silica, and these are strong, durable, and non-absorbent. The best sandstones for building, in England, are obtained from the millstone grit and coal measures, and from the new and old red sandstone formations.

Limestones are of very various texture and quality. Marble is a nearly pure carbonate of lime, hard enough to take a polish Granular and oolitic limestones consist of grains of carbonate of lime cemented by a calcareous or siliceous matrix. Some of these yield excellent, durable, and easily-worked building stone. Generally, however, limestones are softer, more absorbent, and less durable than sandstones. Shelly limestones consist of shells embedded in a more or less crystalline matrix, and some of these are useful as building stone.

Magnesian Limestones, or dolomites, consist of carbonates of lime and magnesia. When properly crystalline in structure they yield a good, easily-dressed, and durable stone. Steatite, or silicate of magnesia, is valuable from its power of resisting fire.

167. *Strength of Stone.*—In most cases stone is used in compression. A block of stone at the base of a pier or in an arch ring is subject to a thrust due to the weight of the structure, and, as far as the condition can be secured the thrust is normal to the faces of the block.

Generally the pressure does not reach 10 tons per sq. ft., though in some lofty structures it reaches 20 to 30 tons, and possibly in some arch rings 40 or 50 tons, per sq. ft. Now, the crushing resistance of stone, tested in small cubes, is seldom less than 250 tons, and often reaches 1,000 tons or more per sq. ft. Hence it has been argued that the strength of stone is of little consequence, its lowest strength being in excess of what is required. It must be remembered, however, that small cubes of stones are selected specimens, more homogeneous and free from defect than large blocks. The cubical form is a stronger one than that of the blocks used in building, and single blocks are stronger than aggregates of blocks. Further, it is quite impossible in any actual structure to secure a simple condition of crushing stress. Settlement, imperfect bedding, unequal compressibility of different blocks, and other causes, introduce unforeseen and incalculable straining actions. Hence, the real factor of safety is not nearly as great as the nominal one

168 *Mode of Crushing in Rigid Materials.*—In ductile materials like wrought iron the mode of yielding to pressure is nearly the inverse of the mode of yielding to tension, and the two resistances are not widely different. But in cast iron and stone and other rigid materials, the tenacity of which is small compared with the resistance to crushing, the mode of yielding is quite different. It has been shown in § 9 that the stress on any oblique plane in a prism subjected to a pressure p in the direction

of its axis may be resolved into a tangential component $p \sin\theta \cos\theta$, and a normal component $p \cos^2\theta$. On a plane making 45° with the axis the intensity of the shearing stress is greatest, and equal to $\frac{1}{2} p$. Now small cylinders of cast iron frequently give way exactly as shown in Fig. 4, and Coulomb inferred that the action was then a simple shearing. But that this is not an exact view of the matter is shown, partly because the inclination of the plane of yielding to the axis often differs a good deal from 45°, partly because the intensity of the stress on the plane of yielding is usually considerably greater than the shearing strength of the material when not in compression. Obviously, the normal component $p \cos^2\theta$ is not without influence on the angle and intensity of stress at which the prism breaks. It produces a frictional resistance to sliding which balances part of the tangential stress. But this, also, is probably an incomplete account of the mode of resistance of rigid materials. The axial pressure and longitudinal compression correspond to a lateral dilatation and transverse tension (§ 1). In some cases stone breaks up into nearly vertical prisms, splitting up at a number of almost vertical planes. In these cases it appears to yield to the lateral tension. Any cause which increases the lateral tension readily produces this kind of fracture, as will be seen presently.

In a square prism there are four symmetrical planes similarly situated with respect to the axis. Hence such prisms frequently yield simultaneously at these four

planes. Thus, a cube breaks into six similar and equal pyramids (Fig. 129; see also Fig. 132). With a rectangular base a prism breaks similarly, but the upper and lower pyramids are terminated by an edge instead of a point. A cylindrical prism shows, *after fracture*, two cones with the sides split off all round. In an even-grained material like sandstone these forms are often very regularly developed.

FIG 129

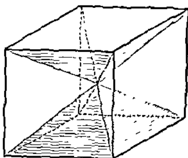


FIG 130

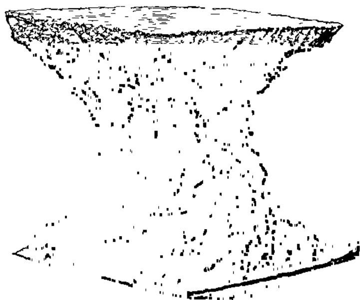
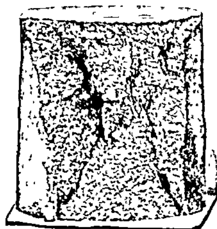


Fig. 130 shows a cube of cement concrete after fracture. Here the pyramidal form of fracture is pretty obvious, in spite of the irregularity of the material. The

middle part, near the apex of the pyramids, is really loose and fissured. Fig. 131 exhibits a cylinder of cement mortar showing very distinctly the conical fracture.

When the height of the prisms is greater than their length of side, the two pyramids which stand on the surfaces at which the pressure is applied are often of unequal height.

FIG. 131



169. *Preparation of Specimens for Crushing.* — The specimens required for crushing may be obtained by sawing, or by dressing with hammer and chisel. It is of the greatest importance that the surfaces at which the crushing pressure acts should be plane and parallel, a requirement sometimes too little attended to. To obtain plane parallel surfaces a planing machine may be used, with a black diamond for a cutting tool; or the surfaces may be ground smooth with emery on a plate of stone or metal. As these processes are troublesome, especially when dealing with bricks, concrete blocks, and other rough material, the author has adopted a plan which is simpler and appears to be quite as satisfactory. When the surfaces are approximately right, they are covered with a thin layer of Parian cement or plaster of Paris which can be easily strickled so as to be plane.

This thin layer does not crush under even the heavy pressures required, and it does not yield or flow. It is, for all practical purposes, a part of the block.

To avoid the trouble of getting parallel plane surfaces, it has been common to make crushing experiments with a layer of pinewood, or lead,[1] or other weak material interposed between the block to be crushed and the cast-iron crossheads of the testing machine The idea has been that the wood or lead distributed the pressure over the surface, and virtually annulled the inequalities of surface. This, however, can be shown to be erroneous. Any weak material may very greatly alter the crushing pressure, and falsify the result of the experiment. It is important that the block to be crushed should be placed directly between the parallel metal surfaces by which the pressure is applied. The only thing the author uses between is a sheet of hard millboard. This is nearly as incompressible as iron, and is not indented by the crushing pressure. It does no harm, and it is doubtful if it does any good. To neutralise, as far as possible, the effect of any want of parallelism of the surfaces of the block and machine, a spherical joint, like that shown in Fig. 105, p. 226, should invariably be used.

170. *Diminution of the Crushing Resistance of Stone when bedded on Lead.*—Twenty years ago it was common, in experiments on crushing, to bed the test specimens of rigid materials like stone on lead plates, with an idea of

[1] In some cases leather has been used, and in some a layer of sand.

securing uniform distribution of pressure on the faces at which the crushing pressure is applied. The author has long had the opinion that to support blocks for crushing on a plastic support is wrong in principle. Hence, in experiments on the crushing of stone and of Portland cement and concrete, he has adopted the plan of preparing the faces on which the crushing pressure acts with a thin layer of plaster. This can easily be worked to smooth and parallel surfaces, which receive the iron plates of the crushing shackles directly, if necessary; but sometimes a sheet of millboard is interposed, which is a very hard and only slightly compressible material. It seemed desirable to try what was the difference of the crushing strength of blocks supported in these two ways. Two series of 4-inch cubes of Portland stone and Yorkshire grit were obtained of very uniform quality. The results of the tests are given below. The great reduction of strength when a thin plate of plastic material like lead is used on the faces to which the crushing pressure is applied is interesting both practically and scientifically. It will be seen that the crushing pressure of blocks between lead plates is in one case only three-fifths, and in another only three-sevenths of that of blocks prepared with plaster and crushed between millboard. One block was cemented carefully between two rigid iron plates with parallel surfaces, and this carried a little more, but only more, load than the block prepared with pl crushed between loose millboards. An exami

the mode of fracture of the blocks shows why the lead has so dangerous an effect on the strength. The blocks crushed between millboards sheared approximately at 45°, forming regular pyramids ; but the blocks crushed between lead broke up into a number of vertical prisms. The lead, flowing under the crushing pressure, produced by friction a tension in the block at right angles to the crushing pressure, and this, added to the tension due to lateral expansion, tore the block in pieces, completely altering the angle of fracture. The pressure of fluidity of lead is from $1\frac{1}{2}$ to 3 tons per sq. in., and these pressures were exceeded in the crushing experiments.

CRUSHING OF STONE BLOCKS, 4 INCH CUBES (APPROXIMATELY)

Description of stone	Crushing load, in tons	Stress, in tons per sq ft	Remarks
Portland ·			
535	57 665	516 38	Between two millboards on each face
536	52 600	469 87	One plate of lead on each face
538	45 65	408 8	One plate of lead on each face, $\frac{1}{8}$ inch smaller than face all round
537	33 50	299 95	Three plates of lead on each face
Yorkshire grit			
539	79 72	712 08	Between two millboards on each face
542	80 05	716 86	Cemented between two strong iron plates with plaster of Paris
540	56 20	504 43	One lead plate on each face
541	35 90	322 27	Three plates of lead on each face

The lead plates were 0 085 inch thick

where A is the area of section of prism, C its circumference, h height of prism, f strength per unit of section, and λ and ν are constants for each material.

It gives at once the law that prisms and cylinders of geometrically similar form have the same strength. Also, that in prisms of the same height and sectional area the strength varies inversely as the square root of the circumference. Thus, prisms of circular, square, and triangular base, of the same height, should have strengths varying as 1 : 0·91 : 0·88. For square prisms of different heights the equation becomes—

$$f = \lambda + \nu \frac{s}{h} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3),$$

where s is the side of the square. According to Bauschinger, this equation is valid up to values of $h = 4s$ or $5s$. This agrees with Vicat's formula. A series of experiments on square and rectangular prisms of different heights, varying from 0·6 to 12 inches, of fine Swiss sandstone, gave the following values of the constant (f, in tons per sq. in.)—

$$\lambda = 239{\cdot}5 \qquad \nu = 292{\cdot}5,$$

when the axis of the prism was parallel to the layers. In another series of experiments on prisms of the same sandstone, crushed perpendicular to the layers, the height, however, not exceeding that of the cube,

$$\lambda = 283{\cdot}5 \qquad \nu = 316.$$

A third series of tests on rectangular and square

prisms of Perlmooser Portland cement, hardened ninety days, gave—

$$\lambda = 139 \qquad \nu = 98{\cdot}6.$$

Tests were made on rectangular and cylindrical prisms, of about 4 inches diameter or length of side and very different heights, cut out of fine-grained Bunter sandstone, and crushed parallel to the layers. These gave—

For prisms . .	$\lambda=317$	$\nu=111$
„ cylinders .	„ 337	„ 105
Mean . . .	„ 327	„ 107·5.

A series of tests with square and rectangular prisms of different heights, having sides with the ratios 1 : 2, 3 : 4, and 1 . 1, also of a fine-grained sandstone, gave—

$$\lambda = 356{\cdot}5 \qquad \nu = 97.$$

Bauschinger shows that the agreement of the equation with the results is throughout satisfactory.

Bauschinger made a further research on the crushing strength of cubes when on one surface the crushing load was confined to a portion of the area Suppose Fig. 133 is the plan of a cube, and that either by bevelling the edges, or by using a small steel pressure-plate, the load is confined to the area of the small rectangle. If o is the centre of the rectangle, and

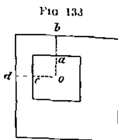


Fig 133

$$o\,b = e_1\,;\ o\,d = e_2\,,\ o\,a = e'\,;\ o\,c = e'',$$

where A is the area of section of prism, C its circumference, h height of prism, f strength per unit of section, and λ and ν are constants for each material.

It gives at once the law that prisms and cylinders *of geometrically similar form have the same strength.* Also, that in prisms of the same height and sectional area the strength varies inversely as the square root of the circumference. Thus, prisms of circular, square, and triangular base, of the same height, should have strengths varying as 1 : 0·94 : 0·88. For square prisms of different heights the equation becomes—

$$f = \lambda + \nu \frac{s}{h} \quad . \quad . \quad . \quad . \quad . \quad (3),$$

where s is the side of the square. According to Bauschinger, this equation is valid up to values of $h = 4\,s$ or $5\,s$. This agrees with Vicat's formula. A series of experiments on square and rectangular prisms of different heights, varying from 0·6 to 12 inches, of fine Swiss sandstone, gave the following values of the constant (f, in tons per sq. in.)—

$$\lambda = 239{\cdot}5 \qquad \nu = 292{\cdot}5,$$

when the axis of the prism was parallel to the layers. In another series of experiments on prisms of the same sandstone, crushed perpendicular to the layers, the height, however, not exceeding that of the cube,

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Tests were made on rectangular and cylindrical prisms, of about 4 inches diameter or length of side and very different heights, cut out of fine-grained Bunter sandstone, and crushed parallel to the layers. These gave—

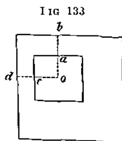
For prisms .	$\lambda = 317$	$\nu = 111$
„ cylinders .	„ 337	„ 105
Mean . . .	„ 327	„ 107·5.

A series of tests with square and rectangular prisms of different heights, having sides with the ratios 1 : 2, 3 : 4, and 1 : 1, also of a fine-grained sandstone, gave—

$\lambda = 356{\cdot}5 \qquad \nu = 97.$

Bauschinger shows that the agreement of the equation with the results is throughout satisfactory.

Bauschinger made a further research on the crushing strength of cubes when on one surface the crushing load was confined to a portion of the area. Suppose Fig. 133 is the plan of a cube, and that either by bevelling the edges, or by using a small steel pressure-plate, the load is confined to the area of the small rectangle. If o is the centre of the rectangle, and



$$o\,b = e_1\,;\ o\,d = e_2\,;\ o\,a = e'\,,\ o\,c = e'',$$

f = crushing pressure per unit of area when pressure is uniform on whole face of cube ; f_1 = crushing pressure per unit of area of pressure-plate.

Then,
$$f_1 = f\sqrt[3]{\frac{e_1 e_2}{e' e''}}.$$

If A and a are the areas of the surface of the cube and pressure-plate, then, when the pressure-plate is central—

$$f_1 = f\sqrt{\frac{A}{a}},$$

If two equal pressure-plates on both faces of the cube are used, then the strength becomes that of the prism of material between the pressure-plates, and is nearly independent of the amount of material surrounding this prism. It is easy to see, therefore, how much a block of stone may be weakened by imperfect bedding.[1]

172. *Determination of the Porosity of Stone.*—Specimens for this purpose should be cubes, and should be well dried. The stone should be brushed, weighed, and then gradually immersed in water. The stone is allowed to remain under water till saturated. It will become nearly saturated in twenty-four hours, but it may, for certainty, be left for five days. It is then taken out, carefully dried on the surface, and weighed. The gain of weight is estimated in per cent. of gross weight. Sometimes the process is hastened by removing the air pressure by an air-pump and allowing it to return.[2]

[1] A similar research by M. Flamant is given in *Ann. des Ponts et Chaussées*, vol. xiv., and *Proc. I. C. E.* vol. xci.

[2] Hatfield. *Trans. Am. Soc. of Civil Engineers*, 1872, p. 145.

For strictly comparable results the specimens should be of the same volume and surface.

POROSITY OF STONES

—	Per cent of water absorbed	No. of hours immersion	Authority
Granites (various)	0 12 1 2	125	Böhme
Syenite	0 50	125	
Porphyry	0 4 2 8	125	"
Granites	0 2 3 0	24	Wray
Trachyte	2 0 4 5	125	Böhme
Slate	51 70	125	"
Roofing slate	0 5	24	Wray
Sandstones (various)	0 7 8 2	125	Böhme
Coal-measure sandstones	1 0 7 0	24	Wray
Old red sandstone	1 6 3 8	24	"
New red sandstone	6 0 10 0	24	"
Lias sandstones	3 0 8 0	24	"
Craigleith	8 0	24	Royal Com
Kenton	9 9	24	"
Mansfield	10 4	24	"
"	2 6 4 8	24	Wray
Limestones (various)	0 31 6 4	125	Böhme
Portland	13 5	24	Royal Com
Ancaster	16 6	24	"
Box ground (Bath)	17 0	24	"
Ketton	15 1	24	"
Chilmark	8 6	24	"
Roche Abbey	17 2	24	"
Oolitic limestones	4 0 12 0	24	"
Shelly limestones (Purbeck)	4 0 2 0	24	Wray
Kent rag	0 5	24	"
Dolomite	1 5	125	Böhme
Magnesian limestone	3 5	24	Wray

The table on next page gives the density and absorption of water of a series of 3-inch cubes of English stone. The blocks were weighed dry and then immersed in water for from seven to fifteen days The weighings were carefully made for the author by Mr H. M. Martin.

Material	Density	Per cent. of water absorbed
Aberdeen granite, red	2·62	0·70
" " grey	2·68	0·81
Clayslate	2·76	0·31
"	2·76	0·23
SANDSTONES		
Red Grinsell	2·16	5·49
White Grinsell	2·15	6·89
Scotgate Head (coal measure)	2·39	3·43
Corse Hill (new red)	2·29	5·05
Robin Hood (coal measure)	2·32	5·41
Hollington	2·19	6·42
Red Mansfield	2·35	4·44
White "	2·30	5·55
Red "	2·37	4·67
Flag-rock Grinsell	2·21	5·08
Red Alton (new red)	2·16	7·43
Derbyshire grit	2·18	6·06
Billstone	2·21	6·03
Howley Park	2·33	4·28
Attleborough	2·02	9·52
Hansworth	2·32	3·84
Duston (ironstone)	2·12	10·10
Ispatria	2·47	8·07
Sydanope	2·16	6·06
Kenilworth	2·06	9·11
LIMESTONES		
White Portland	2·31	8·64
Portland	2·31	5·29
Brown Portland	2·27	6·22
Ancaster	2·15	8·52
Ketton	2·21	9·00
Stoke ground	2·17	8·90
Corsham Down	2·19	9·40
Westwood ground	2·01	12·75
Caen	1·96	12·56
Box ground	1·88	10·10
Church Anson	2·29	6·29
Doulting	2·19	7·40

Resistance to Frost.—The power of resisting frost can be inferred to some extent from the porosity. It is better, however, to saturate a stone with water and then freeze it, repeating the operation ten or more

times. The percentage loss of weight is the measure of the injury done by frost. Brard's test is to immerse the stone for half an hour in a boiling saturated solution of sulphate of soda, and then hang it up for the absorbed salt to crystallize. The process is repeated daily for a week. It is a test of doubtful value.

Resistance to Wear.—The only method of satisfactorily testing the resistance of stone to wear is one devised by Bauschinger. A block of the stone, with a face 4 × 4 inches, is placed on a horizontally-revolving cast-iron plate at a radius of 18 inches. The conditions are found to be most constant when the block is loaded with 66 to 68 lbs. Emery is regularly supplied between the block and plate and cleaned off. The best rate of supply is twenty grams for each ten turns.

173. *Coefficient of Elasticity for Stone.*—The measurement of the compressions and extensions of stone is very difficult, partly from the limitation of size of specimen, partly from the smallness of the deformations, partly from the difficulty of securing uniform distribution of stress. Professor Bauschinger appears to have overcome these difficulties[1] by the use of a modification of his mirror apparatus Plottings to a very large scale of the stresses and deformations show that stone has no elastic limit. It takes permanent sets with very small loads, and the deformation does not increase

[1] 'Uber den Elasticitats-Modul Baustein' *Mitth aus dem Mec Tech. Laboratorium in Munchen.* 1875

at first proportionally to the loads and afterwards deviate from proportionality. For very hard and dense stone the compressions and extensions are indeed initially nearly proportional to the loads, but this remains so up to the breaking stress. For all others, especially for the weaker stones, the greatest departure from proportionality is for the smaller stresses. The greater the loads the more do the deformations approach to proportionality. For sandstone and the less hard granites, the compressions increase first more quickly than the loads and afterwards less rapidly. Hence, the stress strain curve is at first convex and afterwards concave to the axis of loads. With repetition of loading the reversal of curvature gradually disappears.

In the later research on Bavarian stone in 1884, Bauschinger had an opportunity of re-examining the elastic properties of stone with somewhat more perfect test specimens. He found for the hardest stone, and especially limestone, that the coefficient of elasticity was nearly constant, equal for tension and compression, and very large. For most other stone the coefficient of elasticity for tension diminishes with increasing loads. For pressure it sometimes increases with increasing loads, but for the weaker kinds it diminishes at first and then increases.

The stress-strain curves for tension and pressure pass into each other at the origin of co-ordinates without forming a cusp. But three cases are distinguishable: (1) If the coefficient of elasticity is nearly

constant, the two curves for tension and pressure are nearly straight lines and inclined at nearly the same angle to the axis. (2) If the coefficient of elasticity diminishes with increasing loads in tension, the curve is concave to the axis of deformations. Then, (*a*) if the coefficient of elasticity for pressure increases from the beginning, or is nearly constant, the two curves form a regular line always concave in the same direction. But if (*b*) the coefficient of elasticity for pressure diminishes first and then increases, there is a point of contrary flexure at the origin of co-ordinates. Bauschinger is inclined to attribute this appearance to a disintegration of the test block in dressing it by hammer and chisel. The author has obtained measurements of compression of stone similar to Bauschinger's. It seems possible

COEFFICIENT OF ELASTICITY FOR STONE (BAUSCHINGER).

(Stresses and coefficients, in tons per sq ft.)

—	Bending		Tension		Pressure	
	Coefficient E	At a stress of	Coefficient E	At a stress of	Coefficient E	At a stress of
Granite (Metten)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
,, ,, (Passau)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
,, ,,	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Jura limestone (Kelheim)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
,, ,,	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Nummulite limestone	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Bunter sandstone (Phalz)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
,, ,, ,,	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
,, ,, (Wurtzburg)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
,, ,, ,,	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Molasse sandstone (Kempten) . . .	173,000	1·1	116,000	2·2	153,000	1·4
Molasse sandstone (Kempten) . .	43,000	56	29,200	31	240,000	530

that, in a granular substance like stone, the action of the pressure may be to bring the particles to a bearing, and that this may explain the decrease of the coefficient with increase of pressure.

171. *Bauschinger's First Research on the Strength of Stone* ('Mitth. aus dem Mech. Techn. Laboratorium, in München.' 1874).—A few results will be selected from this paper as giving very conveniently the relative resistance to different kinds of straining action. The pressure tests were made on cubes with accurately ground surfaces, on which the cast-iron pressure-plates acted directly. For the shearing strength, three directions of shearing may be distinguished. The shearing plane may be normal to the laminæ, or beds, of the stone, and is then distinguished by the symbol ⊥ ; or it may be in the plane of the beds, and is then indicated by the symbol ∥. Bauschinger experimented in some cases in a third direction also; but these results are omitted. The same symbols apply to the bending experiments, and indicate the position of the plane of fracture.

Bauschinger's Second Research on the Strength of Bavarian Building Stones.[1]—In this series of tests parallelopipeds about 44 inches long and 10 inches × 8 inches square were used for bending tests, with a span of 40 inches. From one of the broken pieces a prism was cut for pressure parallel to the laminæ. From the other, a test piece for tension parallel to the laminæ, and also afterwards for shearing. Cubes were also obtained for

[1] *Mitth. aus dem Mech. Tech. Laboratorium in München.* 1884

STRENGTH OF BUILDING STONES (BAUSCHINGER).

—	Pressure: Crushing stress, tons per sq. ft.	Pressure: Direction of pressure	Shear: Shearing stress, tons per sq. ft.	Shear: Direction of shearing	Bending: Coefficient of bending strength, tons per sq. ft.	Bending: Direction of plane of fracture	Tension: Tenacity, tons per sq. ft.	Tension: Direction of pull
GRANITE								
Coarse-grained grey (Selb, in Oberfranken)	725	⊥	31	⊥	—	—	—	—
" " " "	750	∥	46	∥	—	—	—	—
Black and white of mean coarseness (Hauzenberg)	930¹	⊥	100	⊥	192	⊥	10	∥
" "	940¹	∥	—	—	136	∥	30	⊥
Fine-grained yellow	820	⊥	72	⊥	—	—	—	—
"	—	—	55	∥	—	—	—	—
Hard coarse-grained (St Gotthard)	720	⊥	52	∥	81	∥	25	∥
"	810	∥	—	—	—	—	—	—
Yellow, rather fine-grained (Passau)	850	⊥	83	⊥	84	⊥	20	∥
" " "	850	∥	61	∥	89	∥	17	⊥
LIMESTONE AND DOLOMITE								
White marble (Schlanders, in Tyrol)	820	⊥	—	—		—	—	—
Muschelkalk (Wurtzburg)	400	—	53	—	63	—	25	—
" (Kronach)	1,460	⊥	54	⊥	—	—	—	—
" "	740	∥	43	∥	—	—	—	
Limestone (Pappenheim)	1,000	⊥	61	⊥	—	—	—	—
" "	695	∥	40	∥	—	—	—	—
Dolomite	1,190	⊥	64	⊥	165	⊥	25	∥
" "	1,080	∥	—		—	—		—
" (Konigstein)	600	—	47	—	73	—	9	—
SANDSTONE								
Bunter sandstone (Kronach)	300	⊥	20	⊥	—	—	—	—
" "	174	∥	—	—	—	—	—	—
" " red and fine-grained (Wertheim)	720	⊥	61	⊥	105	⊥	14	∥
" " "	760	∥	—	—	—	—	—	—
Keuper sandstone, red and fine-grained (Wurtemburg)	580	⊥	68	⊥	—	—	—	—
" "	420	∥	47	∥	—	—	—	—
" " white, fine-grained (Coburg)	290	⊥	14	⊥	27	⊥	4	∥
" "	240	∥	12	∥	—	—	—	—
Molasse sandstone, blue, fine-grained (Allgau)	465	⊥	39	⊥	22	⊥	—	—
" " " " " "	—	—	29	∥	—	—	—	—

pressure tests parallel and perpendicular to the laminæ. Some cubes were kept in water, and as opportunity served taken out and exposed to frost. After being frozen about twenty-five times, they were dried, and crushed in a direction parallel to the layers.

STRENGTH OF BAVARIAN BUILDING STONE (BAUSCHINGER).
(Stresses in tons, per sq. ft.)

	Coefficient of bending strength, $\perp$ to bed	Tenacity, $\parallel$ to bed	Crushing strength of prism, 1 : 1 ½	Crushing strength of cubes			Shearing strength	
				$\parallel$ to bed	$\parallel$ to bed after freezing	$\perp$ to bed	$\perp$ to bed	$\parallel$ to bed
Granite (Metten)	87	40	830	1,210	1,380	1,230	88	9
„ (Passau)	77	11	850	1,290	1,310	1,230	93	55
Jura limestone (Kelheim)	30	13 7	226	560	213	{210 / 460}	32	19
Bunter sandstone (Pfalz)	30	7	371	{286 / 455}	135	{435 / 525}	37	23
„ „ (Wurtzburg)	63	40	710	970	780	835	63	35
Green sandstone (Kelheim)	10	6	177	277	260	302	22	21
Molasse sandstone (Kempten)	34	21	615	930		870	43	24
Molasse sandstone (Kempten)	62	33	930	1,120	—	1,850	61	49
Nummulite limestone (Rosenheim)	115	58	1,220	1,320	1,200	1,240	95	73
Diabase (Ochsenkopf)	—		—	2,310	—	2,500	—	—
Lyenite (Wölsau)	—	—	—	1,700	—	1,740	—	—

The following tests were made by Dr. Böhme[1] of cubes about 10 × 10 × 10 inches of rubble limestone masonry, set in different mortars. The cubes were three months old :—

Mortar	Mean crushing strength, in tons, per sq. ft.
1 cement, 3 sand	123 4
1 „ 6 „	69 6
1 cement, 7 lime, 16 sand .	64 3
1 lime, 2 sand	46 5

[1] *Mitt. aus der k. techn. Versuchsanstalt zu Berlin*, 1884, p. 86.

Crushing Strength of Stone.

Description	Tons per sq. ft.	Authority
Granites		
Mount Sorrel	832	Fairbairn
Aberdeen grey (2-inch cube)	1,412	Unwin
,, ,, (cylinder, 2¼ inches diameter, 3¼ inches high)	1,162	,,
Aberdeen red (2-inch cube)	1,614	,,
,, ,, (cylinder, 2¼ inches diameter, 3¼ inches high)	1,357	,,
Quartz	1,270	Mallet
Basalts		
Penmaenmawr (2-inch cube)	1,086	Fairbairn
Hornblendic greenstone	1,580	Wilkinson
Felspathic ,,	1,106	,,
Slates		
Compact Welsh clayslate (3-inch cubes)	733–1,052	Unwin
Slate	1,205	Mallet
Valencia (Irish) (1 inch cubes)	720	Wilkinson
Killaloe ,, ,,	1,974	,,
Sandstones		
Bramleyfall	380	Rennie
Craigleith (2 inch cube)	504	Roy Com
Darley Dale ,,	455	,, ,,
Giffneuk ,,	310	,, ,,
Kenton ,,	318	,, ,,
Morley Moor ,,	318	,, ,,
Park Spring ,,	487	,, ,,
Stanley ,,	383	,, ,,
Runcorn (sixteen 4-inch cubes)	267–443	Unwin
,, (six 3-inch cubes)	295–416	,,
,, (six 4 inch cubes)	427–514	,,
York grit (3-inch cube)	712	,,
Red Mansfield ,,	609	,,
,, ,, (2-inch cubes)	327	Roy Com
White ,, ,,	337	,, ,,
Red Alton ,, (3 inch cubes)	309	Unwin
Sydanape ,, ,,	490	,,
Limestones		
White Italian marble	1,400	Rennie
White statuary ,,	206–389	,,
Portland	239–292	,,
,, (4-inch cube)	516	Unwin
,, (2-inch cube)	250	Roy Com.
Purbeck (1½-inch cube)	587	Rennie

CRUSHING STRENGTH OF STONE—*continued*

Description	Tons per sq. ft	Authority
Ancaster (2 inch cube) .	150	Roy. Com
Barnac ,, . .	114	,, ,,
Ketton ,,	164	,, ,,
,, (3-inch cube)	312	Unwin
Ketton rag (2-inch cube)	577	Roy. Com
Bath, Box ground (2-inch cube)	95	,, ,,
Bolsover (2-inch cube)	484	,, ,,
Bramham Moor ,,	380	,, ,,
Brodsworth ,,	295	,, ,,
Cadeby ,,	104	,, ,,
Chilmark ,,	409	,, ,,
Hamhill ,,	259	,, ,,
Huddlestone ,,	278	,, ,,
Park Nook ,,	278	,, ,,
Roche Abbey ,,	250	,, ,,
Tottenhoo ,,	124	,, ,,
Caen (3-inch cube)	108	Unwin

BRICKS.

175. Bricks are made from clays, loams, or marls containing silicate of alumina, mixed with sand, oxide of iron, and carbonates of lime and magnesia. The plastic, strong, or pure clays contract very much in burning, and do not vitrify, so that the bricks are not durable. Sand diminishes contraction, and permits partial vitrification in burning. Iron acts as a flux, facilitating fusion of the silica, and, in many cases, determines the colour of the bricks. Lime diminishes contraction, and acts as a flux; but lumps of lime become quicklime in burning, and slaking afterwards cause the brick to crack. The following short summary gives the composition of some clays :[1]

[1] *Notes on Building Construction*, Part iii p. 88

Material	[illegible] clay	[illegible]	[illegible]	[illegible]
Silica and alumina	63·3	[illegible]	[illegible]	[illegible]
Oxide of iron	5·0	7·7	[illegible]	[illegible]
Carbonate of lime	18·9	1·1	[illegible]	[illegible]
Carbonate of magnesia	0·1	5·1		[illegible]

Malm is clay mixed with chalk in a wash mill.

Bricks are either hand-moulded or machine moulded. In the latter case the clay may be wet and plastic, or dry or semi-dry. Hand-made bricks have usually a cavity, or frog, on one side, which is supposed to afford a key for the mortar. Wire-cut machine-made bricks have necessarily no cavity or frog. Some pressed bricks have frogs on both sides. Bricks are either 'clamp burned' or 'kiln burned.' The weight of bricks varies a good deal. London stocks weigh about 6·8 lbs. Pressed bricks and blue bricks may weigh 10 lbs. Ordinary red bricks weigh about 7 lbs., while some of the lightest weigh only $5\frac{1}{2}$ to 6 lbs. The absorption of water by bricks also varies. Staffordshire blue bricks absorb 2 to 6 per cent. of their weight; ordinary stocks and red bricks, 7 to 10 per cent.; and the softer and more porous bricks 20 per cent.

The following table gives the crushing strength of a sufficient variety of bricks. It may be added, however, that Mr. Ward gives some tests of bricks of exceptional strength.[1] In these tests, Staffordshire blue bricks carried 650 to 1,064 tons per sq. ft., and bricks made of slate débris 1,056 tons per sq. ft.

[1] *Proc. Inst. of Civil Engineers*, lxxxvi. p. 24.

CRUSHING STRENGTH OF BRICKS (UNWIN).

(Single bricks. Faces made smooth and parallel by plaster of Paris. Crushed between two millboards, or the iron pressure-plates of the testing machine.)

Description	Dimensions, in inches	Cracked, at tons per sq. ft.	Crushed, at tons per sq. ft.	Colour	Remarks
London stock .	4·6 × 4·1 × 2·4	128	177	Yellow	Half-brick
" "	4·6 × 4·0 × 2·45	133	181	"	"
" " .	9·2 × 4·1 × 2·8	—	129	"	
" " .	8·9 × 4·2 × 2·3	—	113	"	
" " .	8·9 × 4·25 × 2·5	—	103	"	
Aylesford, common .	8·9 × 4·4 × 2·7	48	183	Pink	
"	8·9 × 4·4 × 2·7	111	228	"	
" pressed .	9·1 × 4·3 × 2·7	71	141	Red	Deep frog
Rugby, common .	9·5 × 4·2 × 2·9	158	190	"	Between pine boards
" "	9·0 × 4·2 × 3·0	—	120	"	
Lodge Colliery, Notts	9·0 × 4·2 × 3·4	127	159	"	
" " "	9·0 × 4·2 × 3·25	55	122	"	
Digby Colliery, Notts	9·3 × 4·1 × 3·25	218	[353]	"	Not crush'd
" " "	4·6 × 4·2 × 3·2	414	414	"	Half-brick
Ruabon, pressed	8·8 × 4·3 × 2·7	361	[361]	"	Not crush'd
Grantham, wire cut	9·2 × 4·4 × 3·2	–	83	"	
Leicester, wire cut	4·4 × 4·1 × 2·6	251	337	Pale red	Half brick
" " .	4·3 × 4·1 × 2·6	109	308	" "	" "
" " "	9·06 × 4·2 × 2·8	115	229	" "	
Cranleigh, pressed	4·7 × 4·6 × 2·5	149	181	" "	Half-brick, frog
" "	4·6 × 4·6 × 2·5	165	237	" "	Half-brick, frog
Candy, pressed	8·8 × 4·3 × 2·8	80	281		
Gault, wire cut .	8·7 × 4·1 × 3·0	111	173	White	
" " "	4·4 × 4·2 × 2·5	119	115	"	Half-brick
" " "	8·7 × 4·1 × 2·9	—	109	"	
Staffordshire blue, common . .	4·5 × 4·3 × 3·0	216	464	Blue	Half brick
Staffordshire blue, common . .	4·3 × 4·2 × 3·0	152	286	"	" "
Staffordshire blue, common . .	8·9 × 4·3 × 3·1	240	[353]	"	Not crush'd
Staffordshire blue, pressed . .	9·0 × 4·3 × 3·1		275	"	
Glazed brick . .	8·8 × 4·4 × 3·3	69	106		Frog
" " .	8·9 × 4·4 × 2·9	106	174		
Red rubbers, three in column, bedded in putty . .	9·0 × 4·5 × 8·0		25		
Terracotta block .	6 sq. ins		168		
" "	15 " "		139		
" "	15 " "		257		
"	6 " "		104		

176. *Strength of Brickwork.*—Comparatively few accurate tests have been made of the strength of brickwork masses. The following results of tests of brick cubes, with different mortars, were made at Berlin by Dr. Böhme. The brick cubes were approximately $10 \times 10 \times 9 \cdot 5$ inches, and were three months old. Two kinds of brick were used :—

Mortar		[illegible]	[illegible]	[illegible]
		per sq. ft	per sq ft	per sq ft
Beneckendorfer brick				
1 1 lime, 2 sand	Dry	116 2	203 2	11 4
2 7 lime, 1 cement, 16 sand	Dry	130 4	,,	42 0
3 1 cement, 6 sand	Dry	139·4	,,	112 4
4 ,, ,,	Wet	141 9	,,	,,
5 1 cement, 3 sand	Dry	158 8	,,	192 9
6 ,, ,,	Wet	169 8	,,	,,
Hertzfelder brick .				
7 1 lime, 2 sand	Dry	70 0	160 9	11 4
8 7 lime, 1 cement, 16 sand	Dry	73 3	,,	42 0
9. 1 cement, 6 sand	Dry	93 2	,,	112 4
10 ,, ,,	Wet	87 4	,,	,,
11. 1 cement, 3 sand	Dry	100 7	,,	192 9
12 ,, ,,	Wet	104 6	,,	,,

This gives for the ratios of strength of brickwork to strength of single bricks:—

For mortar of 1 lime, 2 sand	0 44
,, ,, ,, 7 lime, 1 cement, 16 sand	0 48
,, ,, ,, 1 cement, 6 sand	0 55
,, ,, ,, 1 cement, 3 sand	0 63

The following experiments on bricks and brickwork pillars were made by Curioni [1] The bricks were placed flat. All the bricks were of the same clay. The mortar

[1] *Proc Inst of Civil Engineers*, lxxiii p 385

consisted of equal parts of Casale Monferrato cement and fine sand, and was allowed fifty days to set:—

Description	Crushing stress, in tons per sq. ft.		
	Hand-made bricks	Machine-made bricks	
		First pattern	Second pattern
Single bricks, between lead	119·8	214·9	142·7
Single bricks, *with faces made even with mortar*	237·8	282·6	211·2
Pillars of 2 bricks, mortar faces	142·6	160·0	142·6
" 3 " " "	86·9	127·1	—
" 4 " " "	—	114·3	—

The reduction of strength by using lead is obvious. If we take the length of a brick to be twice the width and 4 times the thickness, Bauschinger's formula for pillars of this kind takes the form

$$f = a + \frac{b}{n},$$

where f is the strength per sq. ft., n the number of bricks in height, and a and b are constants.

The formula agrees pretty well with the results, if the following values are taken:—

Hand-made bricks . . . $f = 13 + \frac{225}{n}$

Machine-made bricks (1st) $f = 58 + \frac{225}{n}$

" " (2nd) $f = 75 + \frac{136}{n}$

which at least seems to show that the diminution of strength is due to form, and not to influence of the mortar joints.

CHAPTER XV.

LIMES AND CEMENTS.

177. Limes and cements are of the greatest importance to the engineer, and, being artificially manufactured products, they vary in quality according to the care exercised in the selection of the materials of which they are made, and the skill and attention with which the processes of manufacture are carried on. To secure a uniform and trustworthy cement, the engineer has been driven to test regularly the cement supplied. To Mr. Grant is largely due the credit of establishing systematic tests of cement, with the result that, from the pressure brought to bear on manufacturers, and the knowledge gained of the conditions on which the strength of a cement depends, there has been achieved a very considerable and general improvement of quality. In large works, like the Metropolitan Main Drainage, it was perceived that a considerable sum might economically be spent on systematic and regular tests of the quality of the cement supplied. A comparatively large sum spent in testing formed but a small percentage on the value of the cement, and as the quality of cement may vary through very wide limits,

most important industries in this country, in Germany, in France, and in the United States.

Success in its manufacture depends on careful judgment and the rigid observance of essential conditions. It may be produced from a great variety of natural rocks, but, broadly speaking, it consists of 72–79 per cent. of chalk and 28–21 per cent. of clay.

Experience shows the exact proportion of the natural materials used which is most suitable. These materials must be so mixed that the cement is absolutely homogeneous and invariable in composition. At first, the chalk and clay were ground together with a large volume of water into a liquid slip. Now, it is found that grinding with only 35 per cent. of water is *not only economical, but prevents the segregation of* materials which took place in fluid slip. With some materials no water is used in grinding. The mixed materials are then calcined to a clinker at a temperature just short of that which produces fusion or vitrification. Underburned clinker is weak, and overburnt clinker is an almost inert cement. Lastly, the clinker must be broken up and ground to a powder, so fine that the cement particles expose a maximum surface at which chemical actions may occur, and are not too large to fill the smallest inter-spaces in the sand with which the cement is mixed in use.

According to Michaelis, the hydraulicity of a cement is due to the silica, alumina, and oxide of iron. In a good cement the sum of these should be about one-

third[1] of the total weight, the rest being chiefly lime. The calcination removes carbonic acid and water, and leads to the formation of calcium silicate, calcium aluminate, and calcium ferrate. In the setting and hardening of a paste formed of the cement, there is probably a hydration of the silicates, and perhaps the formation of double hydrated silicates.

The composition of a Portland cement varies more or less, but generally lies between the limits given in the following table :—

	Per cent
Silica .	20-26
Alumina	5-10
Oxide of iron	2-6
Lime	67-58
Magnesia .	0 5-3

179. *Ordinary Cement Tests for Strength.*—The ordinary test is a tensile test of a small briquette of neat cement, made in a brass or gun-metal mould, left twenty-four hours to harden in air, and then placed in water. The cement is tested in seven days, and, if possible, at later dates also. At least five briquettes should be tested at each date, and the mean result taken.

The form of the briquettes has a considerable influence on the strength. Fig. 134 shows some of the forms which have been used. Form *a*, used in all the earlier tests, is a very bad form, the square corners producing unequal distribution of stress with a rigid material. The most common form now is *c*, known

[1] In the French rules a cement in which the ratio of silica and alumina combined to lime is less than 0 44 is regarded as doubtful.

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The composition of a Portland cement varies more or less, but generally lies between the limits given in the following table:—

	Per cent
Silica	20 26
Alumina	5 10
Oxide of iron	2 6
Lime	67 58
Magnesia	0 5 3

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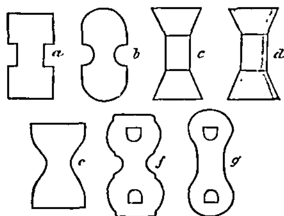
The form of the briquettes has a considerable influence on the strength. Fig. 131 shows some of the forms which have been used. Form *a*, used in all the earlier tests, is a very bad form, the square corners producing unequal distribution of stress with a rigid material. The most common form now is *c*, known

[1] In the French rules a cement in which the ratio of silica and alumina combined to lime is less than 0 44 is regarded as doubtful.

sometimes as Grant's, and this is universally used in Germany. A few engineers use forms like *f* and *g*. A small metal plate is placed in the holes at the ends, and a knife-edge of the shackle passes through each hole.

In some of Mr. Grant's tests, briquettes of the same cement gave strengths ranging from 280 lbs. per sq. in. for form *a*, to 460 lbs per sq. in. for form *c*, at seven days after gauging. For some time briquettes with a sec-

Fig 131



tion of $2\frac{1}{4}$ sq. ins. were used, but it is far more usual now to make the section 1 sq. in. The smaller briquettes are more easily moulded, and give more uniform results.

The briquettes are broken in small lever testing machines, of which there are now many in the market. It is very important that the load should be applied at a regular rate and without shock. Adie's machine is a single-lever machine with a rolling weight. Reid & Bailey's machine is a single-lever machine, with a

mould. The mixing with the trowel should take five minutes, and then the moulds, placed on a glass or slate slab, are filled and rammed and shaken. It is important that the operation should be finished before setting begins.

Mr. Faija has introduced a very convenient cement-gauger, which gauges the cement in less time and more uniformly than it can be done by hand.

The briquettes are removed from the moulds when set, and in twenty-four hours they are placed in water. The temperature during all the operations should, if possible, be 15° to 18° C.

In testing the briquettes, the load should be applied at the rate of 100 lbs. in fifteen seconds.

Briquettes of Sand and Cement.—Briquettes of sand and cement give far more trustworthy indications of the value of a cement than neat cement tests. The cement is always used in construction mixed with other materials, and the cement which is strongest neat is not always strongest tested with sand. The gauging of the briquettes also is easier, and the results are less affected by small variations of procedure. On the other hand, the briquettes must harden twenty-eight days before being tested, and this is in many cases a longer time than can be allowed.

The greatest difficulty of the sand test is securing an identical quality of sand for all tests which are to be compared. A sharp pit sand is best, which should be carefully washed and sifted. The sand used should be

its strength, both the initial strength acquired in a short time and the rate of gain of strength with age require to be considered.

Now, suppose experiments have been made, say, at seven days, four weeks, and twelve weeks. One would still like to be able to predict the strength at a greater age, and even in judging of the data in hand some difficulty arises from the discrepancies and anomalies incident to such experiments, and due to the difficulty of making the experiments numerous enough to get true average values. If anything were known of the law of increase of strength with age, if we could put our results in a formula, their meaning would be much clearer.

Now beyond the first week, and up to a period at which the full strength of the cement is reached, the rate of hardening follows very approximately a simple law. For ordinary tension briquettes, for instance, the gain of strength is nearly proportional to the cube root of the time of hardening, and that both for neat cement and cement mortar. It is possible, therefore, to represent the results of a series of tests in a simple formula, the constants of which indicate the character of the cement with very great clearness.

Let y be the strength of a cement, or cement mortar, in lbs. per sq. in., at an age of x weeks after mixing. From some preliminary tentatives the author found for the relation between x and y the expression—

$$y = a + bx^n \qquad (1),$$

where a, b, and n are empirical constants. In this form the equation would not be very convenient to use, for it would require at least three sets of experiments at three different ages of the test pieces to determine the three constants; and a still greater number would be required for satisfactory results in consequence of the discrepancies which occur in cement testing.

It appeared, however, that for any given kind of cement, and any given kind of straining action, n had a constant value. Further, by a modification of the formula, a might always be the strength of the cement at seven days' age. Consequently there would remain only one constant to determine. The formula then is—

$$y = a + b\,(x-1)^n \quad . \quad (2),$$

where y is the strength of a cement or mortar, at x weeks after mixing, the initial strength of which at seven days is a lbs. per sq. in. The constant n has values which can be assigned beforehand, and only the constant b remains to be determined by experiments on test pieces more than one week old. It will be seen hereafter that, though b varies, its variation is not within very wide limits, so that when the characters of cements are better known it may be possible to assign for it a probable value, even if experiments are wanting in any given case.

Now since in this equation a is the initial strength of the cement, and b a constant, varying with the rate of increase of strength with time, the two con-

stants exhibit very clearly the character of a cement. If their values are determined for any given cement, and inserted in the equation, a numerical equation is obtained which may be termed the characteristic equation for the cement.

181. *Application of the Characteristic Equation to Tension Tests.*—To examine the applicability of the formula, let the constants be determined for the series of tests of Portland cement briquettes extending over seven years given in Mr. Grant's first paper.[1] Mr. Grant's table gives in each case the mean strength of ten briquettes, $2\frac{1}{4}$ sq. ins. in section. In one series the cement was gauged neat; in another series the cement was mixed with an equal weight of clean Thames sand. Mr. Grant's numbers, reduced to lbs. per sq. in., are as follow:—

Age	Strength per square inch	
	Neat cement	1 cement + 1 sand
7 days	363	157
1 month	415	202
3 months	470	241
6 "	523	285
9 "	542	307
12 "	547	320
2 years	590	351
3 "	585	350

Now, for Portland cement in tension, $n = \frac{1}{3}$; the constant a has the values 363 and 157 for the two series,

[1] *Minutes of Proceedings Inst. C.E.* vol. xxv. p. 69, also vol. xxxii. p. 290.

and it only remains to determine the most probable value of b in the equation—

$$y = a + b\sqrt[3]{x-1}.$$

This is best done by calculating b for each of the experiments, except that at seven days, and taking the mean of the values so found. Thus—

NEAT CEMENT

Age x	Strength y	$y-a$	$b = \frac{y-a}{\sqrt[3]{x-1}}$	Strength y by formula
1	363	—	—	363
4	415	52	36	431
13	470	107	47	471
26	525	162	56	503
39	542	179	53	525
52	547	184	49	541
104	590	227	48	588
156	585	—	—	—
	Mean	.	. 48	.

1 CEMENT + 1 SAND

Age x	Strength y	$y-a$	$b = \frac{y-a}{\sqrt[3]{x-1}}$	Strength y by formula
1	157	—	—	157
4	202	45	31	214
13	244	87	38	249
26	285	128	44	274
39	307	150	45	292
52	320	163	44	305
104	351	194	41	345
156	350	193	36	372
208	363			
260	365	Mean .	. 40	

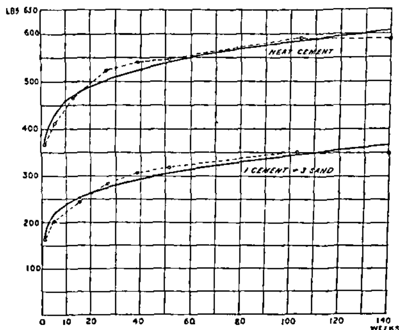
Hence the characteristic equations for this cement and cement mortar are—

Neat cement . . . . . $y = 363 + 48\sqrt[3]{x-1}$

Cement mortar . . . . . $y = 157 + 40\sqrt[3]{x-1}$

Hence, the sand reduces the initial strength of the cement by rather more than one-half (from 363 to 157 lbs. per sq. in.), and the gain of strength at any age is less for the mortar than for the neat cement in the proportion of 40 to 48. By comparing the calculated and observed values of y, it will be seen that the formula

FIG 135.



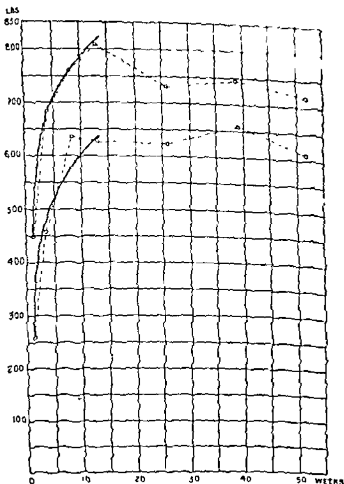
agrees closely enough with experiment for practical purposes. Mr. Grant's figures show that the neat cement reached its maximum strength in one hundred and four weeks, and the cement and sand in one hundred and fifty-six weeks. Hence values of b are calculated from data up to those dates only.

In Fig. 135 the experimental values are shown by

small circles, connected by a broken dotted line, and the calculated values lie on the curves.

In the case of cement mortar the briquettes gain in

FIG 136



strength up to any period to which experiments are usually extended. But with neat cement briquettes a maximum strength appears to be reached, often in

about three months, after which the strength remains constant or slightly falls off. For example, in the experiments given by Mr. Grant on the relative strength of briquettes made on an impervious slab, and on a porous (gypsum) slab,[1] the strength slightly diminishes after thirteen weeks. Hence, for such results the value of b must be deduced from experiments before the maximum is reached, and the formula ceases to apply beyond the maximum. The following characteristic equations were deduced for these experiments from the results for four, eight and a half, and thirteen weeks.

NLAT CEMENT

Impervious slab . . $x = 449 + 161 \sqrt[3]{x-1}$,

Gypsum slab . . $x = 257 + 164 \sqrt[3]{x-1}$

x Weeks	Impervious base		Gypsum slab	
	y Observed	y Calculated	y Observed	y Calculated
1 0	449	449	257	257
4 0	687	681	454	493
8 5	765	765	634	577
13 0	808	819	626	631
26 0	731	—	620	—
39 0	746	—	655	—
52 0	718	—	608	—

These results are plotted in Fig. 136.

182. *Values of Constants for different Cements.*—First some data have been selected from the Table XLVII., p. 169, of Mr. Grant's paper. The only principle of selection adopted was to take those cements for which the completest series of data are given. The following

[1] *Minutes of Proceedings Inst. C.E.* vol. lxii. p. 142.

CHARACTERISTIC EQUATIONS FOR MR. GRANT'S CEMENTS.

(Units lbs. per sq. in., and weeks. Grant's Tests.)

No.	Water used, per cent.	Setting time, in minutes.	Characteristic equation.		Initial strength.	Strength at 13 weeks. Observed.	Strength at 13 weeks. Calc.	Strength at 52 weeks.
1	18·5	Slow	$y = 558 + 96\sqrt[3]{x-1}$		558	615	778	825
12	22·5	15	,, 422 + 118	,,	422	744	692	791
13	20·0	600	,, 614 + 91	,,	614	846	821	813
,,	21·2	,,	,, 610 + 91	,,	610	810	820	779
,,	22·5	,,	,, 520 + 112	,,	520	783	780	772
15	20·0	480	,, 626 − 56	,,	626	824	[illegible]	718
,,	22·5	,,	,, 576 + 140	,,	576	833	806	785
19	22·5	,,	,, 422 + 188	,,	422	793	852	747

The tests of cement which form the most complete series are, however, to be found in the publications of the Engineering Laboratories of Munich and Berlin. In the 'Mitt. aus den Mech. Techn. Laboratorium in Munchen,' for 1879, there is a remarkable series of experiments on the tensile strength of cements, by Professor Bauschinger. In Table II. are given no less than three hundred and sixty results, each the mean of ten separate experiments. Ten different cements were used, and these were made into test pieces of 72 sq. cms. (11 sq. ins.) section. From these results the author obtained the following equations, those for neat cements being deduced from results on test pieces one week to sixteen weeks old, and those for cement and

sand from results on test pieces one week to one hundred and nine weeks old.

The extreme regularity of the constants for a great variety of cements and their limited variation in value is remarkable. The comparatively low initial strength may be partly due to the cement being fresh, partly to the size of the test pieces.

CHARACTERISTIC EQUATIONS FOR TENSILE STRENGTH OF BAUSCHINGER'S CEMENTS

(Units, lbs. per sq in, and weeks)

Cement mark	Setting time, minutes	Neat cement $y =$	1 cement + 3 sand $y =$	1 cement + 5 sand $y =$
A	80	$199 + 40\sqrt[3]{x-1}$	$81 + 29\sqrt[3]{x-1}$	$43 + 31\sqrt[3]{x-1}$
B	49	121 + 49	46 + 36	26 + 30
C	195	199 + 95	108 + 40	78 + 37
D	136	199 + 53	53 + 61	37 + 47
E	13	185 + 42	85 + 40	60 + 28
F	416	256 + 37	112 + 41	67 + 38
G	9 to 17	227 + 64	91 + 40	67 + 33
H	14 „ 26	227 + 36	80 + 46	50 + 36
R	344	299 + 61	136 + 37	105 + 31
T	146	227 + 61	114 + 28	71 + 24
		Mean 54	Mean 40	Mean 33 5

The French official standard of strength for neat cement briquettes is a minimum of 284 lbs. per sq. in. at 7 days, 498 lbs. at 28 days, and 640 lbs. at 84 days after gauging. This agrees nearly with the equation—

$$y = 284 + 155\sqrt[3]{x-1}.$$

The strength is taken to be the mean of the three highest of each set of six tests.

183. *Values of the Constants in Shearing Tests.*—Parts of the briquettes used in Bauschinger's tension tests

given above were subjected to shearing. The following are equations for a few of them :—

Cement mark	Neat cement $y =$	1 cement + 3 sand $y =$	1 cement + 5 sand $y =$
A	$270 + 43\sqrt[3]{x-1}$	$112 + 49\sqrt[3]{x-1}$	$60 + 52\sqrt[3]{x-1}$
B	$142 + 67$	$46 + 53$	$31 + 57$
R	$412 + 57$	$185 + 55$	$131 + 61$
T	242×92	$131 + 43$	$105 + 44$

184. *Characteristic Equation for Tests of other Cementing Materials.*—Some experiments by Dr. Böhme on hydraulic lime have also been examined. These are not very extensive, and they were carried to an age of thirteen weeks only. However, they agree well with a formula of the same general form with $n = 1$. The equation is therefore—

$$y = a + b\,(x-1).$$

The following were deduced from the data :—

Tension ; 1 lime + 1 sand,

$$y = 20 + 11\,(x-1).$$

Tension ; 1 lime + 3 sand,

$$y = 31 + 17\,(x-1).$$

Compression, 1 lime + 1 sand,

$$y = 97 + 44\,(x-1).$$

Compression ; 1 lime + 3 sand,

$$y = 122 + 22\,(x-1.)$$

185. *Fineness of Grinding.*—The greater part of the improvement in the quality of cement which has been effected in the last ten years has been due to the dis-

covery of the importance of grinding the clinker to extreme fineness. The amount of surface the particles of cement expose increases inversely as the diameter of the particles. A cubic inch of cement would have 150 sq. ins. of surface if the particles were spherical and $\frac{1}{25}$ inch in diameter, and 600 sq. ins. if they were $\frac{1}{100}$ inch in diameter; so that the area on which chemical action occurs increases as the cement is ground more finely. But probably this is only part of the explanation of the greater value of very finely ground cement.

If cement is taken and sifted through a sieve of fifty meshes to the inch, the residue on the sieve of particles larger than the holes in the sieve will not adhere together sufficiently to form a briquette. They are almost absolutely without cementitious value. But if these same particles are reground, they are converted into valuable cement.

The extremely small value of these larger particles in the cement was not for some time perceived. For a long time all tests of the strength of cement, or nearly all, were made with neat cement, the reason being that tests of this kind can be made more rapidly than any others. Now, a good cement will bear the addition of a certain amount of inert matter without any sensible reduction of strength; indeed, with a certain gain. Hence it happens that in neat cement tests a somewhat coarsely ground cement gives results higher than a finely ground one. But cement is never, in fact, used neat; it is used mixed with three to seven or more

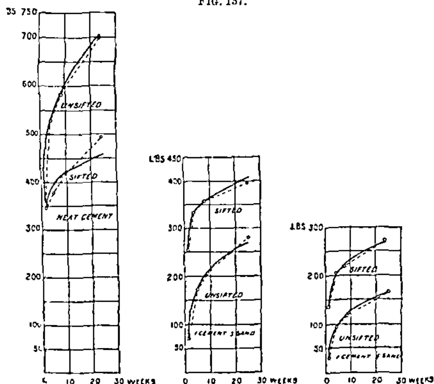
the condition in which it is used in practice, mixed with sand; and directly this was done, it was found that the cements which were strongest tested neat were by no means always strongest tested as mortar mixed with sand. There may be more reasons for this than one, but the principal reason is that the more finely ground cement will bear a considerable addition of sand with less loss of strength than the coarsely ground cement. The coarse cement has, in fact, a proportion of matter as inert as sand already mixed with it.

Suppose a cement has 10 per cent. of inert matter; then, when mixed with sand in the proportion of 2 : 1, the true ratio of cement to inert matter is 1 to 2·33; but if the cement initially contains 40 per cent. of inert matter, then, when mixed with double its weight of sand, the true ratio of cement to inert matter is 1 : 4. It may also be noted that the cement and sand test is to some extent a test of adhesion, the neat cement test being a test of tenacity only.

The fineness of grinding is determined by careful sifting through copper or brass wire sieves with square meshes, and these should be carefully and accurately made. Obviously, in specifying the sieves to be used, it is necessary to state not only the number of meshes to the inch but the size of wire used. The following are the sieves most commonly used in cement-testing:—

	No. of meshes to in.	No. of meshes to sq in.	Diameter of wire
			inches
For cement	25	625	012
,,	50	2,500	·005
,,	74	5,476	0044
,,	100	10,000	·0031
,,	120	14,400	—
,,	180	32,400	—
For sand	20	400	·0146
,,	28	774	·0123

FIG. 137.



The best German cements are ground so fine that they leave a residue of only 3 to 10 per cent on a 76-mesh sieve.[1] English cements are more commonly

[1] The German standard for fineness is that not more than 10 per cent remains on a 76-mesh sieve, the wire of which has a thickness equal to half the width of mesh; ½lb. of cement is used for this test.

specified to pass entirely through a 25-mesh sieve, and to leave not more than 10 per cent. on a 50-mesh sieve.

Fig. 137 shows the results of a series of tests by Messrs. Dyckerhoff, given in Mr. Grant's paper. The same cement was used in all the tests; but in one series the cement was used as manufactured, in the other after sifting through a fine sieve. The former left 10 per cent. on a 50-mesh sieve; the latter all passed through a 180-mesh sieve.

The equations corresponding to the curves in the diagrams are as follows:—

Neat cement.

Neat unsifted cement—

$$y = 353 + 122\sqrt[3]{x-1}$$

Neat sifted cement—

$$y = 346 + 36\sqrt[3]{x-1}$$

1 *cement* + 3 *sand.*

Cement unsifted—

$$y = 75 + 69\sqrt[3]{x-1}$$

Cement sifted—

$$y = 252 + 53\sqrt[3]{x-1}$$

1 *cement* + 5 *sand.*

Cement unsifted—

$$y = 31 + 46\sqrt[3]{x-1}$$

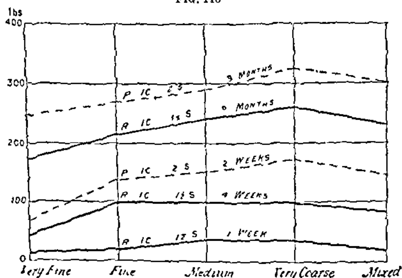
Cement sifted—

$$y = 136 + 47\sqrt[3]{x-1}.$$

A series of experiments, given in Mr. Elliot Clarke's very interesting 'Report on the Boston Main Drainage

inverse reason that fine cement is good. Fine cement coats a large surface, and fits well into the interspaces of the sand. Large-grained sand has less surface to coat, and its spaces are more easily filled with cement. Now, uniform size of grain may be obtained by sifting. Standard Berlin sand is passed through a 20- and is retained by a 28-mesh sieve. But sands of uniform size

FIG. 110



of grain do not make equally good mortar. Two sands sifted through and retained on the same sieves give different tests. There is something in the form of the grains and the kind of space between them—possibly even something in the chemical condition of the sand—which affects the initial strength and rate of hardening of the briquette. These different qualities are shown very clearly in the following characteristic equations,

deduced from experiments by Mr. Arnold, at the Harbour Works at Wilhemshaven. The tests are 1 cement to 3 sand, the same cement used throughout :—

Wilhemshaven blue sand, fine-grained and sharp—

$$y = 101 + 22\sqrt[3]{x-1}$$

Dangast normal sand, sifted in the same way as Berlin normal sand, not very sharp—

$$y = 124 + 23\sqrt[3]{x-1}$$

Dangast common building sand—

$$y = 165 + 13\sqrt[3]{x-1}$$

Wangeroog, coarser, clean and sharp—

$$y = 193 + 41\sqrt[3]{x-1}$$

Berlin normal, clean sharp quartz sand—

$$y = 250 + 44\sqrt[3]{x-1}$$

188 *Influence of Proportion of Sand on the Strength of the Mortar.*—Cement mortars are weaker than neat cement, probably because the adhesion of the cement to the sand is less than the tenacity of the cement. The larger the proportion of the sand, the weaker the mortar. It appears that, even with a proportion of 1 cement to 3 sand, the whole of the interstices of the sand cannot be filled with cement, and as the proportion of sand increases the proportion of unfilled space must increase, and therefore there must be a less section to break.

From a series of tests, by Mr. Elliot Clarke, of about 500 briquettes, all made with the same cement

(the tests extending over two years), the following very uniform series of equations are obtained :—

PORTLAND CEMENT MORTAR, WITH DIFFERENT PROPORTIONS OF SAND (BOSTON).

Neat cement	$y = 303 + 61\sqrt[3]{x-1}$
1 cement + 1 sand	$160 + 57$,,
1 ,, + 2 ,,	$126 + 44$,,
1 ,, + 3 ,,	$95 + 36$,,
1 ,, + 5 ,,	$55 + 26$,,

Below are given the results of experiments by Dr. Böhme on the influence of the addition of various substances to cement. Some of these, such as gypsum, have been added at times with an idea that they improved the cement ; others have been added occasionally as adulterations. Slacked lime has sometimes been used with cement in very cold weather. It will be seen that, with the exception of sifted cement, every one of these additions reduces the strength of the cement :—

PORTLAND CEMENT WITH VARIOUS ADDITIONS (BOHME).

(A, Cement ; B, Sifted cement, C, Fine sand ; D, Slag, E, Brick-dust, F, Slack-lime.)

Mixture	Neat	1 cement to 3 sand
100A	$y = 583 + 88\sqrt[3]{x-1}$	$y = 199 + 48\sqrt[3]{x-1}$
90A + 10B	$498 + 93$	$213 + 45$
90A + 10C	$526 + 69$	$128 + 65$
90A + 10D	$469 + 77$	$128 + 59$
90A + 10E	$452 + 107$	$137 + 58$
90A + 10F	$514 + 71$	$155 + 48$
50A + 50F	$262 + 88$	$82 + 44$

189. *Determination of the Setting Time.*—The roughest means of determining the time in which a cement sets is to observe when a flat pat can no longer be indented by the finger-nail. A more accurate method is to use a

loaded needle or wire. Perhaps the French standard test is as definite as any. The cement paste, as soon as possible after gauging, is filled into a metal box $1\frac{1}{2}$ inch deep and 3 inches diameter. Over this is suspended, by a pulley and balance weight, a needle of $10\frac{1}{2}$ oz. weight, with a square section of 1 sq. mm. (side of square, 0·04 inch). The cement is said to have taken initial set when the needle fails to penetrate the whole depth if lowered gently on it, and final set when its surface just supports the needle. A cement commencing to set in less than 30 minutes, or setting finally in less than three hours from commencement of gauging, is rejected. For certain purposes quicker cements are useful. In America a needle $\frac{1}{12}$ inch in diameter, loaded with $\frac{1}{4}$ lb., and a needle $\frac{1}{24}$ inch in diameter, loaded with 1 lb., are used to determine setting time

Effect of Time of Setting on the Qualities of a Cement.—There is a prevalent opinion that quick-setting cements do not continue long to gain in strength, but reach a maximum, and then fall off, or diminish in strength. This curious diminution in strength, often shown in experiments, may be due to minute and imperceptible cracks, but perhaps it is rather an error of testing than a real loss of strength The cement, no doubt, gets more brittle, and that has the effect of making the test more difficult, and increasing the chance of breaking the briquette with a load rather less than the real tenacity.

Mr. Grant has given a table of tests of quick and

(the tests extending over two years), the following very uniform series of equations are obtained :—

Portland Cement Mortar, with Different Proportions of Sand (Boston)

Neat cement	$y = 303 + 61\sqrt[3]{x-1}$
1 cement + 1 sand	$160 + 57$,,
1 ,, + 2 ,,	$126 + 44$,,
1 ,, + 3 ,,	$95 + 36$,,
1 ,, + 5 ,,	$55 + 26$,,

Below are given the results of experiments by Dr. Böhme on the influence of the addition of various substances to cement. Some of these, such as gypsum, have been added at times with an idea that they improved the cement; others have been added occasionally as adulterations. Slacked lime has sometimes been used with cement in very cold weather. It will be seen that, with the exception of sifted cement, every one of these additions reduces the strength of the cement :—

Portland Cement with various Additions (Böhme).

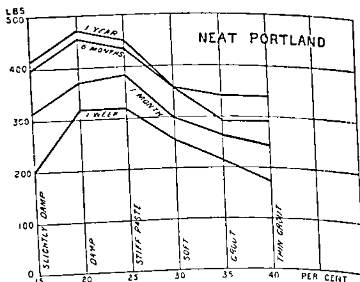
(A, Cement; B, Sifted cement, C, Fine sand, D, Slag, E, Brick-dust: F, Slack-lime)

Mixture	Neat	1 cement to 3 sand
100A	$y = 583 + 88\sqrt[3]{r-1}$	$y = 199 + 48\sqrt[3]{r-1}$
90A + 10B	$498 + 93$	$213 + 45$
90A + 10C	$526 + 69$	$128 + 65$
90A + 10D	$469 + 77$	$128 + 59$
90A + 10E	$452 + 107$	$137 + 58$
90A + 10F	$514 + 71$	$155 + 48$
50A + 50F	$262 + 88$	$82 + 44$

189. *Determination of the Setting Time.*—The roughest means of determining the time in which a cement sets is to observe when a flat pat can no longer be indented by the finger-nail. A more accurate method is to use a

water must be used in gauging cement or cement mortar, which varies with the character of the cement. The finest ground and quickest cements require most water. Now, unfortunately, every drop of water added beyond what is necessary weakens the cement, and this is the chief source of the discrepancies which occur in cement-testing. In purely commercial testing it is naturally

FIG 141.



and not unfairly desired to get the best result possible out of the cement. In this country the briquettes are moulded on an impervious slab of slate or marble or glass. The cement is gauged neat with the least amount of water which will permit moulding, and the very stiff paste into which the cement is formed is pressed into the moulds as rapidly as possible. To get uniform results the water used must be very accurately measured.

It varies from 18 to 25 per cent. of the weight of cement.

In Fig. 141 are shown the results of some experiments at Boston, on the same cement, mixed with different proportions of water. The greatest strength is obtained with between 20 and 25 per cent. of water. The proportionate difference of strength as the time of hardening increases is less; so that it is for short, one-week tests that the quantity of water makes the greatest difference.

191. *Test for Soundness.*—One of the most dangerous qualities of a cement is a tendency to blow or crack after setting, in consequence of expansion due to the chemical actions which are going on. Expansion of this kind, producing cracks, is commonly due to the presence of unslacked lime in the cement; gypsum added as an adulteration is open to the same objection. These substances are the more dangerous that they rather add to than detract from the strength of the cement, and hence escape detection by the ordinary test.

That Portland cement does expand in hardening may be shown easily by filling lamp glass chimneys with the cement, and placing them for hardening in water. With both neat cement and cement and sand the chimneys invariably crack about the third day, and in the course of ten days the glass is cracked all over.

The ordinary test for soundness is to make a pat or cake, 2 or 3 inches in diameter and $\frac{1}{2}$ inch thick, with thin edges, and place it in water. If the cake, in

hardening, shows any tendency to crack or contort, the cement is dangerous.

It is often extremely important to determine the soundness of a cement in a shorter time than this process requires. Now, heat accelerates greatly the hardening process, and hence sometimes the pats of cement are placed on an iron plate heated by a gas jet. Then any tendency to crack shows itself in a short time. This may be called the baking process. Tetmajer recommends that a pat 4 inches diameter and $\frac{3}{8}$ inch thick should be baked in a drying chamber at 120° C. for three or four hours.

A still better process is to heat the pats in a steam bath. Mr. Faija makes a convenient apparatus, consisting of a double bath with regulated gas jet. The water in the outer bath is kept at 110°, and the pats are placed at first on a slip of glass in the steam, in the inner bath, in vapour at about 100°. After five or six hours the pat is hard enough to be placed in the water, and may be kept cooking for twenty hours. If at the end of that time the pat is still adherent to the glass, and without cracks, the cement is perfectly sound.

German Standard Test.—The minimum tensile strength of briquettes of 1 cement to 3 sand by weight, after hardening 1 day in air and 27 days in water, is $227\frac{1}{2}$ lbs. per sq in. The crushing strength is 2,275 lbs. per sq. in.

192. *Measurement of Expansion of Cement.*—Bauschinger took cubes of cement of 4·8 inches length of side.

Twenty-four hours after mixing, a small brass plate, about $\frac{4}{10}$ inch diameter, was fixed into two opposite sides of the cube, by cementing. After forty-eight hours' hardening, the accurate measurements between the brass plates were commenced. The cube was placed in a measuring instrument, having a spring touch-lever on one side and a micrometer screw on the other. The touch-lever ensured the constancy of pressure between the measuring points and the block to be measured. The pitch of the screw was very accurately determined; and as a perfectly constant temperature cannot be insured in experiments lasting a long time, a correction for the expansion of the cement blocks by heat was determined.

Neat cement briquettes hardened in air sometimes showed a small expansion at first, but all ultimately shrank in volume. Neat cement briquettes hardened in water all showed a very small expansion, generally less than ·05 m. in 120 mm. length in sixteen weeks. With briquettes mixed with sand the changes of volume were of the same kind, but smaller.

Quickness of Loading.—I believe Mr. Faija first pointed out that the rate of loading a briquette affected the breaking weight. The quicker a briquette is loaded, the greater the load which can be got on before it gives way. In some definite experiments, Mr. Faija found a difference of 23 per cent. in the breaking weight of exactly similar briquettes, broken quickly and broken slowly. It is now generally recommended that the weight should be added at the rate of 100 lbs.

in fifteen seconds.[1] Mr. Adie has devised an ingenious arrangement for regulating the speed of loading. Mr. Deacon, I believe, puts half the probable breaking weight on the briquette, and leaves it twelve hours, and then completes the test.

193. *Tests by Pressure.*—Almost all that has been said thus far relates to the ordinary mode of testing cements and cement mortars by tensile stress. That mode of testing was adopted for mere reasons of convenience. The cement has only about one-tenth the strength in tension which it has in compression. Hence, for tension tests a small, cheap, easily managed testing machine can be used. For compression tests, the testing machines must be much larger and more costly. But as a matter of fact cement is but little used in positions in which its resistance to tension is in play. The most important works in which cement is used are expressly designed to avoid tension in any part. If, indeed, in some positions structures are exposed to the possibility of tensile strains, due to failure of foundations or backing, still the tensile stresses so developed are small compared with the normal crushing stresses for which the structure is designed.

Tension tests having been adopted, and being convenient no doubt, find defenders. Broadly speaking, a cement with high tenacity will be strong to resist crushing; but the correspondence in the resistance to

[1] The German rate of loading is ¼ lb per second, the briquettes being 0 775 sq ins. section.

the two kinds of stress is far from exact. Bauschinger has found that the ratio of resistance to crushing to resistance to tension varies from eleven to one to seven to one; and that the order of merit for cements tried for tension is not the same as the order for crushing. It has even been said that crushing tests are useless and inaccurate. If they have proved so, it is only because the proper conditions of accurate testing have been neglected. In Bauschinger's tests of 5-inch cubes, the results are considerably more uniform than the tests of the same cements in small briquettes by tension.

In proper crushing experiments two conditions must be fulfilled, which have hitherto been too much neglected in crushing experiments. (1) The faces of the block on which the crushing pressure acts must be plane parallel surfaces. (2) The crushing pressure must be uniformly distributed on those surfaces.

In moulded blocks of cement or cement concrete the surfaces are hardly ever as parallel as is desirable. The surfaces are generally more or less rough, and more or less warped. By striking over the faces a thin layer of gypsum or Parian cement, which sets immediately, perfectly plane and parallel faces can be obtained, without in any way altering the strength of the block. Weak as these cements are, thin layers stand the crushing pressure perfectly. To ensure the equal distribution of the crushing pressure on the faces it is only necessary, in a properly constructed testing machine, to interpose a spherical joint between the block and the face of the machine.

It may be useful to examine if the rate of hardening in pressure tests can be expressed as simply as that in tension tests. In Bauschinger's paper already referred to there are a series of pressure tests of the same series of cements as that used in the tension tests.

The test pieces were cubes of 144 sq. cms. (22·3 sq. ins., or 4·75 inches length of side). Either from the large size of the cubes, or the nature of the stress, or some other cause, it is necessary to take $n = \frac{1}{2}$ in the general equation, instead of its value for tension. With this change, the equation fits the compression results satisfactorily. The equation for compression is therefore—

$$y = c + d\sqrt{x - 1},$$

where y is the compressive strength in lbs. per sq. in. at x weeks after mixing.

The equations obtained from Bauschinger's results are as follow, the equations being all applicable to an age of two years at least :—

Cement mark	Neat cement $y =$	1 cement + 3 sand $y =$	1 cement + 5 sand $y =$
A	$1,877 + 206\sqrt{x-1}$	$953 + 299\sqrt{x-1}$	$469 + 299\sqrt{x-1}$
B	953 + 227	313 + 248	199 + 199
C	1,991 + 490	1,038 + 313	740 + 305
D	1,770 + 327	427 + 412	284 + 313
E	1,592 + 341	668 + 320	356 + 263
F	2,404 + 299	625 + 334	540 + 284
G	1,582 + 270	782 + 270	483 + 249
H	1,436 + 334	711 + 270	341 + 256
R	2,631 + 441	1,507 + 341	995 + 341
T	1,920 + 455	1,024 + 313	626 + 227
	Mean 339	Mean 312	Mean 274

Tests of Nine-inch Cubes of Portland Cement Concrete.

(When the block did not crush the greatest load is given in brackets. The dates in the second column are taken from Mr. Deacon's letter.)

No. of block	Date of moulding	Date of testing	Mean horizontal dimensions	Mean section	Load at which first crack was observed	Crushing load	Time between moulding and testing	Crushing pressure	Crushed between	Remarks
			Inches	Sq ft.	Tons	Tons	Months	Tons per sq ft		
7	Nov. 1882	Nov. 30, 1885	9·02 × 8·93	·550	90·3	103·6	36	185·4	Millboards	[not crushed
8	Dec. 1882	Dec 3, 1885	8·95 × 8·96	·557	—	[104·52]	35	[187·6]	,,	Parian cement on top face,
9	Jan. 1883	Dec 1, 1885	8·96 × 9·02	·561	—	[101·16]	34	[185·7]	,,	Ditto, not crushed
11	Mar 1883	Nov. 28, 1885	8·93 × 8·99	·558	72·05	100·6	32	180·3	,,	
3	May 1883	Nov. 12, 1885	9·02 × 8·95	·563	82·23	91·12	29½	161·8	,,	
4	June 1883	Nov. 12, 1885	9·05 × 9·05	·569	41·80	81·08	28½	142·5	,,	
5	June 1883	Nov 13, 1885	8·82 × 9·02	·552	89·30	[100·10]	28¼	[181·3]	,,	Badly cracked, not crushed
6	Sept. 1883	Nov. 13, 1885	8·98 × 9·00	·561	29·35	62·69	23½	111·7	,,	
12	Dec 1883	Dec. 2, 1885	9·05 × 9·05	·569	94·86	99·51	23	174·9	,,	Parian cement on top face
13	Mar 1884	Nov 27, 1885	9·00 × 9·01	·565	54·00	92·4	20	163·6	,,	
14	June 1884	Dec 2, 1885	9·06 × 9·02	·568	99·50	106·33	17	187·2	,,	,,
18	June 1885	Nov. 28, 1885	9·02 × 9·02	·565	51·27	69·73	5	122·4	,,	
19	Sep 1885	Nov. 28, 1885	9·03 × 9·03	·566	40·41	51·30	2	90·6	,,	
20	Sep. 22, 1885	Dec. 8, 1885	9·02 × 9·02	·565	50·10	63·32	77 days	112·10	,,	
21	Sep 29, 1885	Dec. 8, 1885	9·02 × 9·02	·565	32·30	47·61	70 ,,	84·23	,,	,,
22	Oct. 14, 1885	Dec. 9, 1885	9·01 × 9·02	·564	44·50	53·52	56 ,,	94·90	,,	,,
23	Oct 27, 1885	Dec. 9, 1885	9·01 × 9·03	·567	61·97	64·68	43 ,,	114·10	,,	,,
24	Nov. 4, 1885	Dec. 9, 1885	9·02 × 9·02	·565	60·50	60·51	35 ,,	107·10	,,	,,
25	Nov. 11, 1885	Dec. 9, 1885	9·02 × 9·02	·565	61·75	80·21	29 ,,	141·99	,,	,,

Here the first constant, which can be obtained by tests lasting one week only, varies a good deal; but the second constant has no very great range of variation about its mean values. If the initial strength of the cement is known therefore, the strength at any age up to two years can be inferred with a certain degree of approximation.

Strength of Concrete.—The table on opposite page, from the Report of Mr. G F. Deacon on the Vyrnwy Masonry Dam, gives the strength of a series of nearly cubical blocks of Portland cement concrete, made at various dates during the progress of the work.

The following summary gives a general view of the average strength at different ages:—

Age of block, in months	Main strength, in tons per sq. ft
32-36	over 180
28½-29½	162
17-25½	159
2-5	102
1-2	114

The blocks prepared with Parian cement to ensure a plane face give rather higher crushing pressures than the others. Some blocks cut out of the work itself gave crushing pressures somewhat greater still.

Detection of Adulteration.—The means of detecting adulteration of cement have been examined by Drs. R. and W. Fresenius Adulteration by lime is shown by too low a specific gravity, great loss by ignition, high alkalinity of aqueous solution, and too great absorption of

carbonic anhydride. An adulteration by slag is shown by slightly lowered specific gravity, lowered alkalinity, and by the large amount of chamaeleon solution which may be added. The details of the methods of testing are given in a paper abstracted recently for the Institute of Civil Engineers.

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